APPENDIX E -- PRELIMINARY RESULTS OF THE LOXAHATCHEE ESTUARY HYDRODYNAMICS/SALINITY MODEL

Contents

1. Introduction

The upstream migration of salt water into the historic freshwater reaches of the Loxahatchee River has altered the floodplain cypress forest community along the Northwest Fork and some of its tributaries. A hydrodynamic/salinity model was developed to study the influence of freshwater input on the salinity conditions in the river and estuary. The purpose of this modeling effort was to predict salinity conditions at various points in the estuary with respect of freshwater inflow rates and tidal fluctuations. The two-dimensional hydrodynamic/salinity model was also used to provide a preliminary assessment on the impacts of inlet deepening and sea level rise on the salinity regime in the estuary.

During model development, it was apparent after initial data review that a more coordinated data collection program in the study area was needed. A data collection plan was developed in 2001. The data collection project obtained the Governing Board approval in September 2002. The instrument installation has begun in the field. It is expected that the first patch of data will be available before the end of 2002.

In order to meet the MFL study schedule, parallel with the data collection plan development, the hydrodynamic model was developed in a 6-month time frame using available data. The model will be revised when a new and more complete data set becomes available.

The model was calibrated and verified against field data that were collected from January to June of 1999. Then the model was applied to scenarios that were proposed by the study team. Two series of model simulations were requested. The first simulation (Simulation #1) included flows from the Northwest Fork of the River and its three tributaries based on flow ratios established by a previous study. The second model run was named Simulation #2 and contained a minimum amount of freshwater input from the three tributaries. Simulation #1 was used to predict salinity conditions with various freshwater inflow rates that follow historic freshwater input patterns. The purpose of Simulation #2 was to predict salinity condition on a "worst case" scenario with the Northwest Fork of the river providing the majority of water with minimum freshwater input provided by the three tributaries to the estuary.

These model results were used to provide an estimate of the volume of water needed from the Northwest Fork of the river to maintain salinity within the range that was recommended by biological studies. Model simulation indicates that there is a strong correlation between freshwater inflow and salinity regime in the estuary. Based on this relationship, a computer program was developed to provide an estimate on the historic salinity conditions at eight sites in the Northwest Fork.

This document outlines the basic model setup, assumptions and calibration/verification process. A summary of preliminary results of model applications is presented.

2. Model Description

2.1. Computer Model (Software) Description

The software used in the development of Loxahatchee River Hydrodynamics/Salinity Model were computer programs RMA-2 and RMA-4 that were developed by Army Corps of Engineers (USACE, 1996).

RMA2 is a two dimensional depth averaged finite element hydrodynamic numerical model. It computes water surface elevations and horizontal velocity components for subcritical, free-surface flow in two dimensional flow fields. RMA2 computes a finite element solution of the Reynolds form of the Navier-Stokes equations for turbulent flows. Friction is calculated with the Manning's or Chezy equation, and eddy viscosity coefficients are used to define turbulence characteristics. Both steady and unsteady state (dynamic) problems can be analyzed.

The program has been applied to calculate water levels and flow distribution around islands; flow at bridges having one or more relief openings, in contracting and expanding reaches, into and out of off-channel hydropower plants, at river junctions, and into and out of pumping plant channels; circulation and transport in water bodies with wetlands; and general water levels and flow patterns in rivers, reservoirs, and estuaries.

The water quality model, RMA4, is designed to simulate the depth-average advection-diffusion process in an aquatic environment. The model is used for investigating the physical processes of migration and mixing of a soluble substance in reservoirs, rivers, bays, estuaries and coastal zones. The model is useful for evaluation of the basic processes or for defining the effectiveness of remedial measures. For complex geometries, the model utilizes the depth-averaged hydrodynamics from RMA2.

The formulation of RMA4 is limited to one-dimensional (cross-sectionally averaged) and two-dimensional (depth-averaged) situations in which the concentration is fairly well mixed in the vertical direction. It will not provide accurate concentrations for stratified situations in which the constituent concentration influences the density of the fluid. The preliminary results indicated that the model was able to predict the salinity fluctuation driven by the tide cycle and the influence of freshwater input on the salinity regime in the river. On the other hand, since the model only simulates the water movement in the horizontal direction all the output is depth-averaged. The model does not simulate the stratification that exists in the system. While the whole system is driven by the horizontal salinity gradient between the ocean and freshwater, there could be some density-induced circulation locally that could not be simulated. The South Florida Water Management District has started a data collection program in Loxahatchee River that would provide field data for the development of a 3-D model that can simulate currents and transport in 3-D environment including stratified systems.

2.2. Data Sources and Assumptions

RMA-2 and RMA-4 are two-dimensional models that are based on the real topography of the modeling area. In addition to the geographic data, the model also requires flow and tide data to form the boundary conditions. The model requires freshwater inflow data at all tributaries and tide data on the ocean boundary. Wind, precipitation and evaporation have not been included in the study at this stage. These factors will be included in the second phase of the model development when field data is available.

2.2.1 Bathymetric data

Bathymetry for the model development was provided by the Florida Department of Transportation. The original survey report has not been located. Since the data was produced by a recent survey in 1999, it was assumed that the datum of the survey data was NAD 83 and NAVD 88. While the bathymetric data fit well with other data in NAD 83 and NAVD 88, the data datum is still to be confirmed by the original report or a report that describes the survey data.

The bathymetric data does not cover the upstream portion of Northwest Fork above river mile 4. The approximate channel depth was based on a bathymetric map produced by USGS in 1982 (McPherson, Sabanskas, & Long, 1982) and lead line measurements by the district staff.

2.2.2 Model Datum

The model was developed in North America Datum 83 (NAD83) and North America Vertical Datum 88 (NAVD88). All the XY coordinates are in State Plane Florida East.

2.2.3 Surface Freshwater Inflows

Surface water inflow records were needed for model calibration and verification period January through June 1999. Flow records for that period at S-46, Lainhart Dam and Kitching Creek were retrieved from the South Florida Water Management District database DBHYDRO. Flow data of Cypress Creek, Hobe Grove, and North Fork for the same period was not found. A previous study (Russell and McPherson, 1983) conducted by USGS analyzed two years of the flow record and calculated the relative magnitude of freshwater inflow from each tributaries of the Loxahatchee river. The flow ratios between tributaries provided in the USGS report were applied to the calibration/verification period to estimate the freshwater flow from Cypress Creek and Hobe Grove. The upstream model boundary is the Florida Turnpike. Freshwater inflow at this location was estimated based on the flow record at the Lainhart Dam and an incremental ratio derived from the USGS data set.

2.2.4 Groundwater Inflows

One of the major tasks of model calibration was to estimate the magnitude of groundwater input to the system. Based on flow and salinity record of a dry period in May 1999, it was estimated that there was approximately 40 cfs groundwater input to the upstream portion of Northwest Fork above Kitching Creek. Groundwater seepage into the river depends on the groundwater table and the stage of the river. Before a formula is established for groundwater calculation, a constant 40 cfs was applied to model verification and subsequent scenario simulations. The district is in the process of developing an integrated surface/groundwater model that can calculate groundwater in put to the system more accurately.

2.2.5 Tide Data

Tide is a major driving force of the system. Since no measured tidal data is available for the model calibration/verification period, an ocean tide model developed by Army Corps of Engineers (Scheffner, 1994; Borgman and Scheffner, 1991) was applied to generate the time sequence of tide heights. The time sequence of tide heights at 30 minutes intervals were generated by the model for an off shore location near Jupiter Inlet at Latitude North 26.94998, and Longitude West 80.04684. The tide heights were generated based on 8 tidal constituents, K1, O1, P1, Q1, N2, M2, S2 and K2.

In the model calibration process, the model output was compared with the NOAA tide book. The NOAA tide table has predicted tides for 10 locations in Loxahatchee River and its tributaries. The latitude and longitude in NOAA Tide Table (NOS, 1998) were converted to State Plane Florida East with conversion software *CORPSCON 5.11.08* developed by U.S. Army Topographic Engineering Center.

The ocean model, NOAA Tide Table and the bathymetric data use different vertical datum. The ocean model output generates tide heights relative to mean tide level. The NOAA tide table provides tide height in mean lower low water. The model output is in NAVD88. To compare with model output, tide data have to be converted to the same geodetic datum NAVD88. A research of NOAA tidal benchmark record located two benchmarks that are related to NATIONAL GEODETIC VERTICAL DATUM-1929 (NGVD29). At NOAA tide site North Fork Entrance, 0 NGVD is at 0.59 FEET MLLW. At South Jetty of Jupiter Inlet, 0 NGVD is at 1.2 FEET MLLW. In the model calibration process, the model output and NOAA data were compared at absolute elevation at these two sites. For other stations, the comparison was only on tide amplitude.

In the process of model calibration, the tide data generated by the ocean model was adjusted to reflect the amplitude attenuation over the shelf and the difference between the vertical datum NGVD29 and MTL. With a conversion formula of

$$\text{ModelBoundaryTide} = \text{OceanTide}*0.7+0.88',$$

the model output at South Jetty of Jupiter Inlet would match the NOAA predicted tide. This conversion of ocean tide was applied to all the simulations in the subsequent model simulations and produced results that are consistent with NOAA predicted tides.

2.2.6 Salinity Data

Salinity data was provided by the Loxahatchee River District for the period of record January 1994 - July 2000. Sampling equipment consisted of three Hydrolab Datasonde Model #3 monitoring probes and a data logger unit. This equipment provided readings for salinity (specific conductivity) dissolved oxygen, depth and other parameters. Data were recorded at one half hour intervals.

2.3 Model Calibration and Verification

During model development, it was apparent after initial data review that a more coordinated data collection program in the study area was needed. A data collection plan was developed in 2001. The data collection project obtained the Governing Board approval in September 2002. The instrument installation has begun in the field. It is expected that the first patch of data will be available before the end of 2002.

In order to meet the MFL study schedule, parallel with the data collection plan development, the hydrodynamic model was developed in a 6-month time frame using available data. This section describes the process of preliminary model assessment. The model will be revised when a new and more complete data set becomes available.

2.3.1 Preliminary Calibration and Verification against Field Data

4736 topographic data points are derived from survey data of Loxahatchee estuary to form the model grid/mesh. The XY coordinates and elevation of the 4736 points form the geometry of the model. Figure 1 is the finite element model mesh that was developed for Loxahatchee Estuary salinity study.

Accurate salinity prediction is based on the accurate prediction of tides. Hydrodynamic calibration and verification in tide simulations lays the groundwork for salinity simulations. The hydrodynamic model was calibrated against NOAA data for a three-month period from December 1996 to February 1997. Then the tidal output was verified against NOAA data for a four-month period from January 1999 to April 1999. Tide verification results are presented in subsequent sections.

Salinity model calibration was based on flow and salinity records from January 1 to April 30, 1999. The period includes a typical transition from wet season to dry season. While the flow record at Lainhart Dam shows a decreasing freshwater inflow to the estuary, the salinity records indicate that the salinity went up significantly even at the upstream portion of the estuary. Figure 2 and 3 are comparisons between model output and the field records at Station 64 (River Mile 7.7) and Station 65 (River Mile 8.6).

Model verification was based on the field records of the subsequent two months - May and June 1999. Starting in May, the freshwater inflow increased and salinity level dropped accordingly. Model output was depicted with two different colors in Figure 3. The first portion was the model calibration result. The second portion was the model verification result. The verification result was also compared with field data at Station 66 Hobe Grove (River Mile 9.4) as presented in Figure 4.

2.3.2 Comparison with Existing Regression Models

In addition to preliminary model calibration and verification that was outlined previously, the model was compared with three regression models that were based on field data. Two regression models were developed by district staff. The other regression model was developed by Gary Russell and Ben McPherson of USGS in 1984.

a. Comparison with SFWMD (Linton) Regression Models

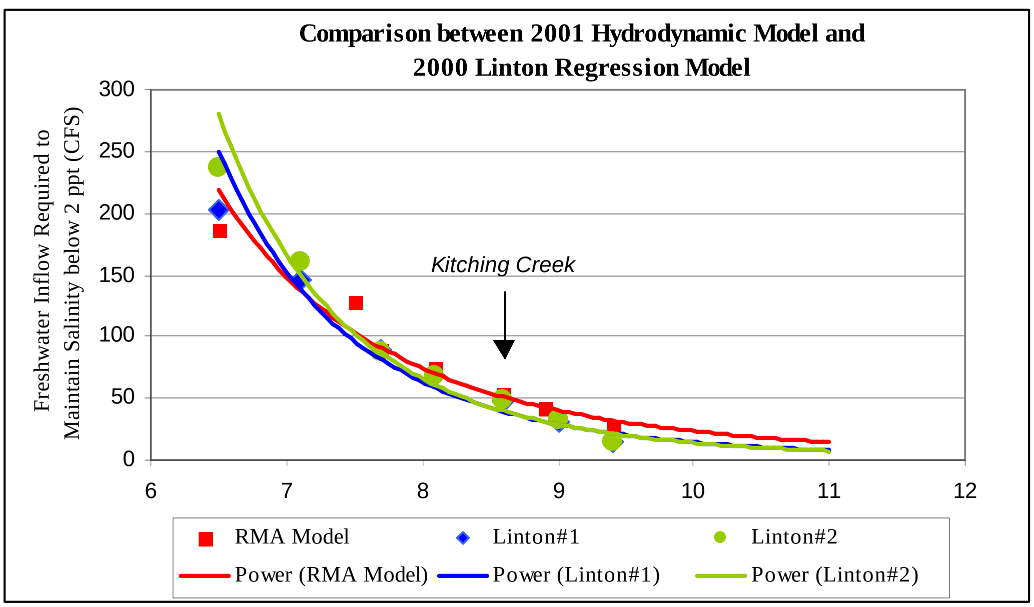

Chart 1. Comparison of hydrodynamic model with Linton regression model

Before the hydrodynamic model was developed, district staff developed two regression models that describe the freshwater inflow and salinity relationship in 1990s both before and after several river restoration projects were implemented. In Chart 1, the relationships produced by the two regression models were compared with the results of the hydrodynamic model. The hydrodynamic model produces results that reflect factors such as tide regime changes between spring and neap tides, transition between salinity regimes and daily salinity fluctuation due to tides. The model results were averaged and simplified in Chart 1 so that it can be compared directly with regression models that do not simulate the dynamic processes. The MFL study has been focused on river reaches above the Kitching Creek, the comparison seems to indicated that the hydrodynamic model result is on the conservative side (requiring more freshwater) among the three models.

b. Comparison with USGS Regression Model (Russell & McPherson, 1984)

In early 1980s, USGS conducted the most extensive and the best-documented investigation in the history of Loxahatchee River study. Freshwater inflow was measured on all the major tributaries for a period of two years from February 1980 through March 1982. The two-year period included both dry and wet periods and the Tropical Storm Dennis in the August of 1981. Tide and salinity measuring instruments were deployed in both main channel and tributaries. The instrument calibration was verified each day before and after field measurements. Based on this comprehensive concurrent data set, Russell and McPherson developed a regression model that describes the relationship between the freshwater inflow and the salinity level in the river. In Chart 2, the relationship was presented in blue color with freshwater inflow versus the position of 2 ppt salinity line in river miles. The same relationship that was produced by the hydrodynamic model is plotted in red color for purpose of comparison.

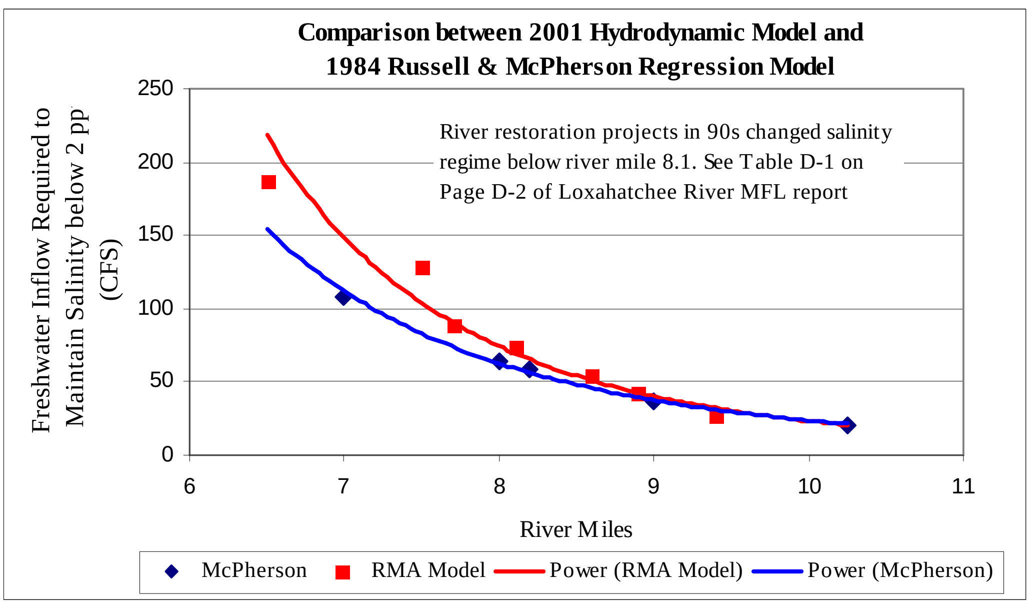

Chart 2. Comparison of 2001 hydrodynamic model and 1984 USGS regression model

The geometry of the hydrodynamic model was based on a bathymetric survey conducted in 1999. The model was also calibrated using flow and salinity measurement in 1999. Therefore the 2000 hydrodynamic model reflects the 1999 condition of the river. On the other hand, the Russell & McPherson model that was based on data collected in early 80s, documented the historic condition that existed almost two decades ago. It is interesting to see how these two models would compare.

The comparison in Chart 2 indicated that the two models gave approximately same results for river reaches above Kitching Creek. The differences over the downstream reaches were possibly due to the changes in the geometry of the river channel over the two decades. Major changes taking place in the period were river restoration projects in the 1990s.

A separate field data analysis was carried to verify the impact of river restoration projects on salinity regime. Relationships between flow and saltwater wedge position was developed based on field measurements from the period both before and after the restoration projects were implemented. Then the two relationships were compared. The results indicated that, while the flow difference at river mile 6.5 can be as high as 33 cfs, the impact on the river reaches above river mile 8.1 is as small as 1 to 2 cfs. (Table D-1, Page D-2 of Loxahatchee River MFL Report, July 15, 2002 Draft). Above river mile 9.4, no differences were detected. The comparison of the 2002 hydrodynamic model and the 1984 USGS model in Chart 2 seems to confirm the findings described above.

The analysis of both 2000 hydrodynamic model and 1984 USGS regression model results indicates:

1. The difference between the two models below Kitching Creek was probably due to the changes in the river (such as several river restoration projects) between early 1980s and 1999.
2. The two models give almost identical results for river reaches above the Kitching Creek. This seems to indicate that the flow ~ salinity relationship in this part of the river has not changed significantly in the period between early 1980s and late 1990s.

The Loxahatchee MFL study has been focused on the river reaches above the Kitching Creek. The fact that the 1984 regression model and the 2000 hydrodynamic model are producing very similar flow vs. salinity relationship for river reaches above the Kitching Creek is significant. We will come back to this point later in this section.

c. Comparison with SAS Regression Results

The district staff also conducted regression analysis on data from three stations with SAS. While the statistic analysis with SAS was continuing, some early results were presented in Loxahatchee River MFL Report, July 15, 2002 Draft (Page D-11 through D-22). The SAS curve in the draft report indicates a higher freshwater demand at Station 64 when compared with other modeling results and analysis.

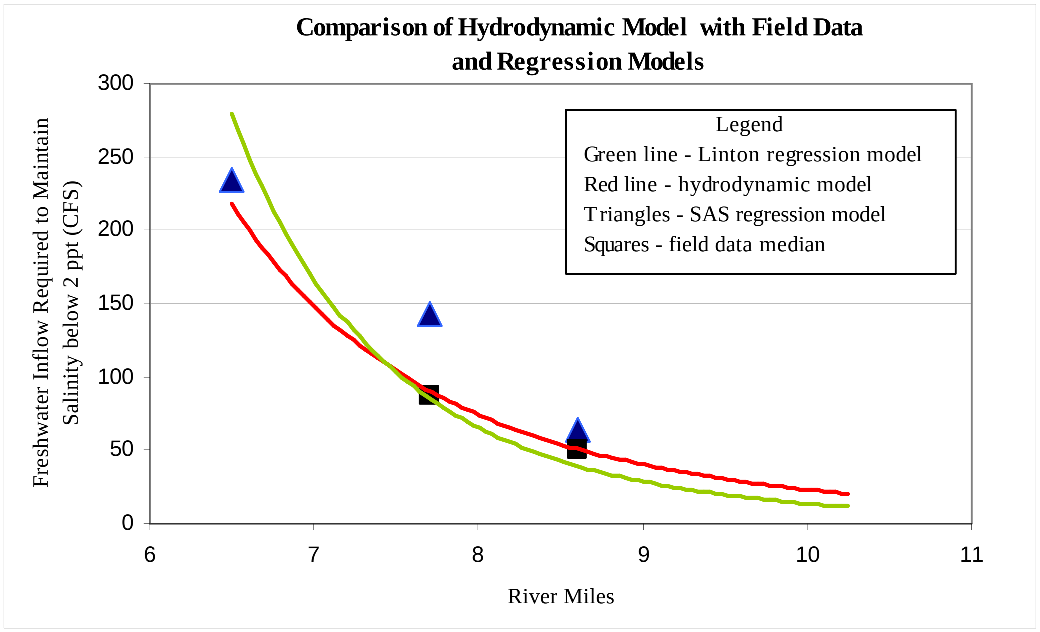

Chart 3. Comparison of SAS analysis with other regression models and the hydrodynamic model

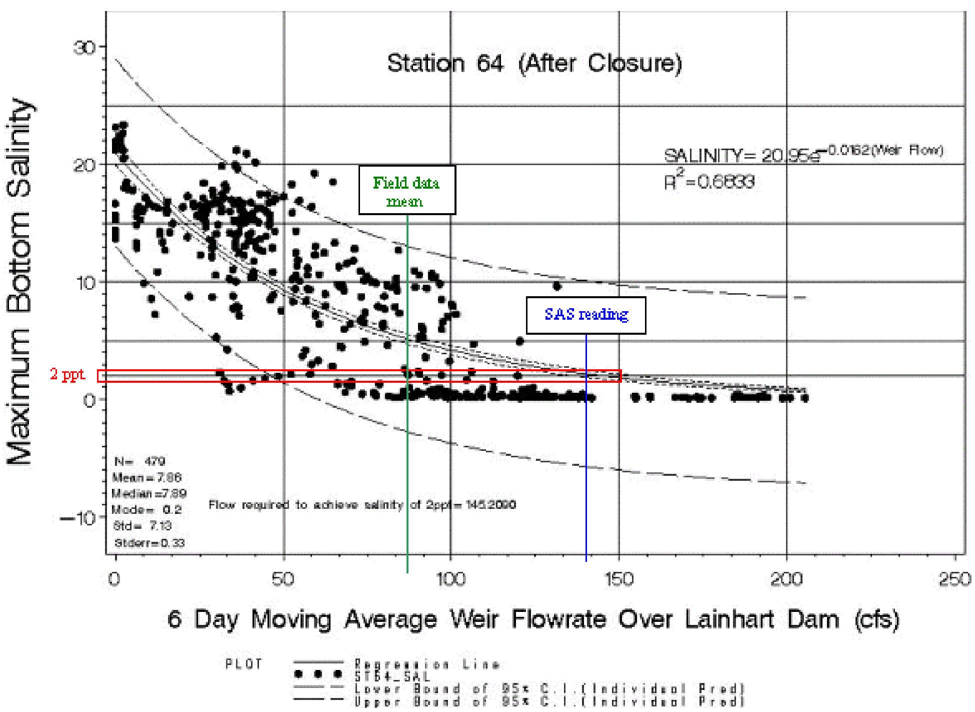

Chart 4. Examination of a regression chart on Page D-18 of the July 15, 2002 draft MFL report

Chart 3 is a comparison of SAS results with Linton regression model and the hydrodynamic model. The SAS results are consistent with other models except at Station 64. At Station 64, SAS seems to indicate a higher demand of freshwater to maintain salinity below 2 ppt. An examination of the original analysis is illustrated in Chart 4. If the regression curve in Chart 4 is compared with the dots on the chart that represent original field data it becomes apparent that, while the curve gives a decent fit on a very scattered data set, the curve does not fit the field data well in the low salinity range. In the area below 4 ppt, all data dots fall below the curve. It is difficult for a regression model to fit all the field data well over the entire data range. Apparently the curve in Figure 4 does not fit field data well in the 2 ppt salinity range. The blue line in the figure illustrates how a 140 cfs reading could have been obtained from the regression curve from the point it intersects with the 2 ppt horizontal line that is marked with red lines. All the data points along the 2 ppt line fall on the left hand (smaller) side of the curve. The 140 cfs reading from the curve is larger than any field data points. A good fit regression model should predict a value that is close to the mean or median value of the field data. The median value of the field data that fall between 1.5 ppt and 2.5 ppt at Station 64 is 87.6 cfs. The other regression model (Linton model) predicted a freshwater demand of 87 cfs. The hydrodynamic model predicted a demand of 89 cfs. Both are in close range of field data median. In order to achieve a better fit in the low salinity range, more regression analysis with SAS has been conducted. Using the same function type, when analysis is on data between 0 ppt and 10 ppt, the regression curve intersects the 2 ppt line at 100 cfs that is much closer to the field data median. Chart 5 is plotted with the revised SAS regression result. This chart might be further revised when the SAS analysis is finalized.

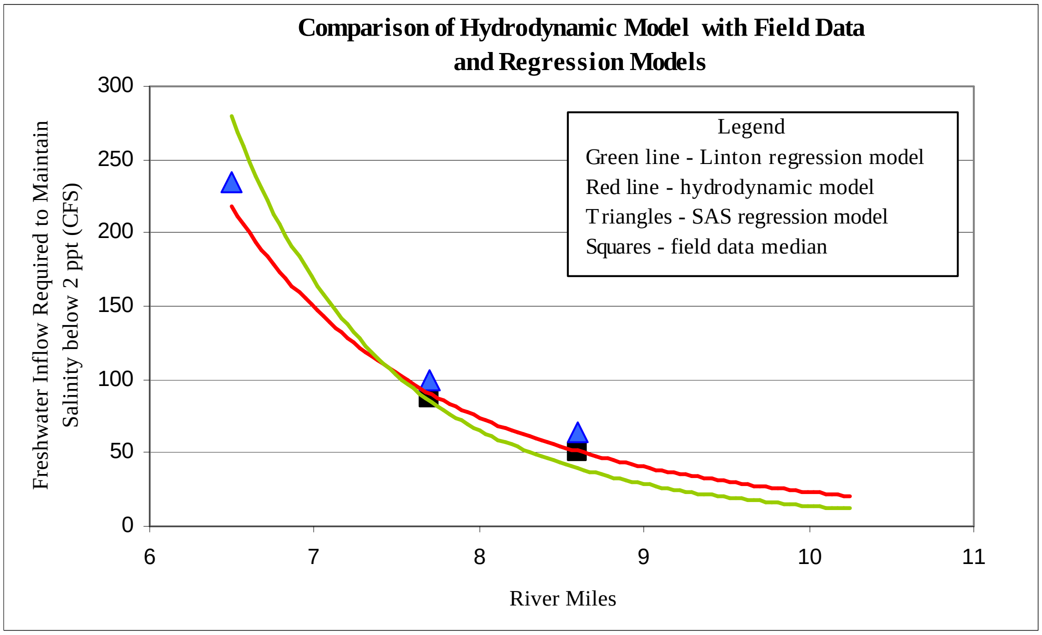

Chart 5. Comparison of new SAS analysis with other regression models and the hydrodynamic model

2.3.3 Preliminary Model Assessment

Since the hydrodynamic model was based on recent data, it is necessary to assess the changes in the river that have taken place in the past decades and how that would affect the accuracy of the model applications.

While the development of a watershed model is underway to assess the changes in hydrology over the past decades, it is safe to assume that some changes took place in the watershed that would have affected hydrology. The hydrodynamic model is an estuary model. The model itself does not simulate watershed hydrological process nor produce the amount of freshwater input to the estuary. Freshwater inflow is provided to the model in the form of model input. Therefore when historic flow record was used in model simulation, the historic flow condition under historic hydrology was reflected in the flow input files.

Besides changes in the watershed, there have also been changes in the river. Most visible of these changes is the implementation of river restoration projects (such as the closing of gaps between oxbows). District staff analyzed field data from the periods both before and after the river restoration projects. Comparison of the flow ~ salinity relationship from the two periods indicates a detectable difference for river reaches below river mile 8 (Table D-1, Page D-2 of Loxahatchee River MFL Report, July 15, 2002 Draft). There was no detectable changes in flow ~ salinity relationship for rivers above river mile 8. Comparison between 2000 SFWMD hydrodynamic model and 1984 USGS regression model led to the same conclusion as discussed previously.

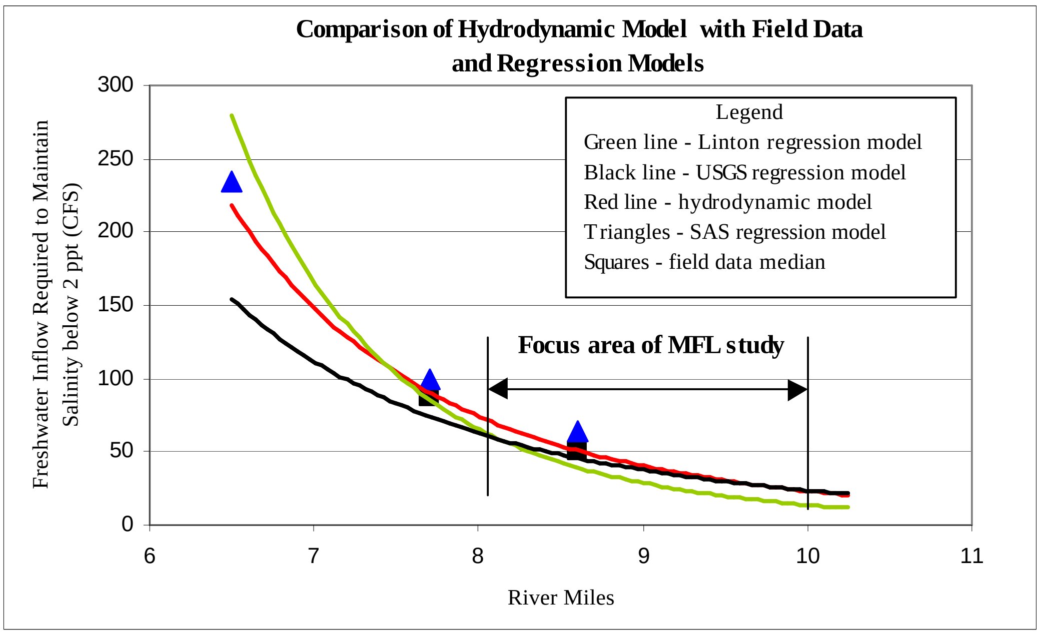

Chart 6. Comparison of all available models and field data median

A more comprehensive review of historic field data is currently underway. All the analysis that have been completed so far has not detected any significant difference in flow ~ salinity relationship above river mile 8, which is the focus of the current MFL study.

Loxahatchee Estuary is a very dynamic, tide driven system. While changes in freshwater affect salinity, tide makes salinity change at a more rapid pace. Even in the upper Northwest Fork, daily salinity variation can be 10 ppt or more between high tide and low tide. Tide regime change between spring and neap tides also affect salinity greatly. These are factors that make regression analysis difficult to obtain a clear freshwater flow ~ salinity relationship. This is the main reason that data points in the regression analysis are so scattered, which reduce the confidence level of regression results. On the other hand, a hydrodynamic model can simulates all the tide-related factors in addition to freshwater inflow.

Another underlining assumption of all the existing modeling effort including both hydrodynamic model and regression models is the assumption that total freshwater inflow is proportional to the flow at Lainhart Dam. Flow data analysis indicated that this flow ratio assumption is valid on long term basis. But apparently this ratio will vary greatly on daily basis. Along with the on going MFL study, a data collection network is being deployed in the river and the watershed. This network will provide a comprehensive and CONCURRENT data set. More improvement to the models will be implemented when new data becomes available.

Both hydrodynamic models and regression models are important tools in this study. Each type of model has its own advantages and shortcomings. Regression models, while they are not capable of complicated dynamic simulations, are important tools as a reality check since they are usually empirical in nature and therefore have more direct links with field data.

MFL study was based on the “best available data” approach. The analysis outlined above compared the hydrodynamic model with all other available regression models as a reality check. The analysis indicates that the hydrodynamic model output was consistent with regression model results.

The district staff is working on more regression analysis with SAS. The SAS results for Station 63 and 65 that appeared in this memo are the early preliminary results presented in Loxahatchee River MFL Report, July 15, 2002 Draft. They will be revised when final results are available.

In river reaches below Kitching Creek, it appears that there is a difference between models that were developed based on recent data and the USGS regression model that was based on early 1980s condition. The current MFL study focuses on reaches above the Kitching Creek where all models appear to converge to a narrow band. This seems to indicate that the flow ~ salinity relationship in reaches above the Kitching Creek has been relatively stable.

3. Model Application Results

3.1 Tides

The hydrodynamic model was calibrated against NOAA data for a three-month period from December 1996 to February 1997. Then the tidal output was verified against NOAA data for a four-month period from January 1999 to April 1999. This section describes the basic characteristics of tides in the Loxahatchee Estuary.

3.1.1 Semidiurnal Tidal Cycle

Both field data and the model simulation indicate strong tidal influence to the system. Semidiurnal tidal cycle has two highs and two lows each day with about 6 hours between each high and the next low. The semidiurnal tides generate flooding and ebbing in the estuary and cause salinity fluctuations. This tidal influence can be detected even at the far upstream portion of the Northwest Fork of the River. Figure 5 is the salinity record at Station 65 located at River Miles 8.6 of the Northwest Fork for March 31, 1999. Salinity was recorded as below 1 ppt at low tide at 4 am and increases to over 7 ppt at high tide at 10 am. Another pair of low and high occurred at 16:00 and 22:00.

3.1.2 Monthly Tidal Cycle

Monthly tidal cycle includes two spring tides and two neap tides. Spring tides of increased range between high water and low water occur semimonthly as the results of the Moon being new or full. Neap tides of decreased range occur semimonthly as the result of the Moon being in quadrature. Figure 6 compares the NOAA predicted tide with Loxahatchee model output at station BoyScoutDock. In the four months period, there are eight spring tides and eight neap tides in between. (The spring tide at the beginning and the end of the period make one complete spring tide and is counted as one.)

3.1.3 Comparison of Model Tide Output and NOAA Predicted Tide

Before the salinity model was calibrated and verified, the model was calibrated and verified to ensure that the hydrodynamic model can generated tides correctly. Since no continuous tidal record has been located for the model calibration and verification period, the model output was compared with NOAA Tide Table. Figure 6 presents both model output and NOAA predicted tide at station BoyScoutDock. This station is the most upstream (inland) station that is listed in the NOAA Tide Table. Model output was also verified against data of other NOAA sites at Middle and Lower Estuary and at the Jupiter Inlet.

3.2 The Influence of Freshwater Input on the Salinity Regime in the Estuary

3.2.1 Response Time

The estuarine salinity regime is the result of a dynamic process that involves mainly tides and freshwater inflow. Transition of estuarine salinity regime occurs constantly in response to the changes in tides and freshwater inflow. Even if the freshwater inflow is constant, there is a significant variation in salinity within each tidal cycle. On the other hand, daily average salinity does tend to reach a quasi-equilibrium state if freshwater inflow is steady. There is a time lag (response time) between the time of freshwater inflow change and the time when salinity adjustment is completed. If freshwater inflow is steady after the adjustment, daily salinity variation will stay within a fixed range with the same highs and lows everyday. At this point it is said that the salinity condition has reached a new equilibrium. Comparing a continuous concurrent flow and salinity record helps understand the response time of the system. Figure 7a is flow and salinity record for a 10-day period in April 1999. Salinity at Station 65 (River Mile 8.6) went up by about 7 ppt after a 30-cfs freshwater input decrease at the Lainhart Dam.

Since the difference between the spring tide and the neap tide has a significant impact on salinity levels, the salinity changes due to freshwater input changes are often overshadowed by tide regime transition. To further investigate the salinity response time, a model simulation was designed. The mean tide range of 2.46' was applied to the entire simulation so that the impact of freshwater inflow rate can be detected clearly. Figure 7b is the model output for three locations in the Northwest Fork. Although there are certain variations in response time in field data, they appear to be mostly completed within a 10-day time window. This is consistent with the model output in Figure 7b. The speed of transition is proportional to the magnitude of the difference between the current condition and the anticipated equilibrium condition. Therefore a large portion of salinity adjustment takes place in the early stage of the transition. While it takes about 8 to 10 days to complete the salinity regime transition and reach a new equilibrium completely, 90% or more of the changes appear to be completed in 5 to 6 days.

3.2.2 Relationship between Freshwater Input and Salinity Regime in Northwest Fork

Modeling Approach

The estuary receives freshwater input from numerous sources; it is necessary to find a surrogate that could represent the freshwater input level. Due to the lack of data for groundwater and flow from other tributaries, the model calibration was based on the historic flow record at Lainhart Dam to estimate the total freshwater input to the system. While the model was not able to repeat all the fluctuations over the 6-month period, it did reproduce the general trend rather accurately. This seems to confirm that the flow rate at Lainhart dam can be used as a surrogate of overall freshwater input amount. This also shows the potential that the discharge at Lainhart Dam could be a management target. In the model simulations described below the total freshwater input was linked to the discharge at the Lainhart Dam with the flow ratios that were applied in model calibration and verification.

Another indicator was needed to describe the salinity condition at certain sites. Considering that the tidal range variation between spring and neap tides is another major factor that affects the salinity, a 28-day tidal cycle with two spring tides and two neap tides was chosen for all the flow scenario simulations. The model predicts salinity for each of the over 3000 nodes at 30 minutes intervals. To reduce the amount of information for analysis at this level, the model output was filtered to select high tide and low tide salinity only. Then the 56 high tide salinity and 56 low tide salinity were averaged to find the mean high tide salinity and the mean low tide salinity for the 28-day period. This data retrieval and processing was completed for 13 sites in the Northwest Fork, the middle and lower estuary, and at the inlet.

Freshwater Flow Scenarios

Two series of model simulations were conducted. Simulation #1 was developed using calculations of flow data for tributaries based on flow ratios applied in model calibration and verification. In contrast, Simulation #2 consists of a flow scenario with minimum amount of freshwater input from the three tributaries. Simulation #2 was considered the worst case scenario while Simulation #1 was developed to predict salinity conditions at various freshwater input levels that follow historic pattern. 10 cfs groundwater input was added to the Northwest Fork and its three major tributaries based on the model calibration results. Table 1 through Table 3 listed the flow scenarios of Simulations #1 and #2.

Table 1. Freshwater Input of Simulation #1 (without groundwater input)

RunSeries	LainhartDam	LOXTnpk	Trappers	CypressCrk	HobeGrv	KitchenCrk	NWFTotal	NF	S46
1	200	233	279	131	29	16	455	4	500
2	200	233	279	131	29	16	455	4	5
3	150	174	209	98	21	12	341	4	5
4	100	116	140	65	14	8	227	4	5
5	85	99	119	56	12	7	193	4	5
6	65	76	91	42	9	5	148	4	5
7	50	58	70	33	7	4	114	4	5
8	40	47	56	26	6	3	91	4	5
9	30	35	42	20	4	2	68	4	5
10	20	23	28	13	3	2	45	4	5
11	10	12	14	7	1	1	23	4	5
12	10	12	14	7	1	1	23	4	10
13	20	23	28	13	3	2	45	4	10

Table 2. Freshwater Input of Simulation #1 (with groundwater input)

RunSeries	LainhartDam	LOXTnpk	Trappers	CypressCrk	HobeGrv	KitchenCrk	NWFTotal	NF	S46
1	200	233	289	141	39	26	495	4	500
2	200	233	289	141	39	26	495	4	5
3	150	174	219	108	31	22	381	4	5
4	100	116	150	75	24	18	267	4	5
5	85	99	129	66	22	17	233	4	5
6	65	76	101	52	19	15	188	4	5
7	50	58	80	43	17	14	154	4	5
8	40	47	66	36	16	13	131	4	5
9	30	35	52	30	14	12	108	4	5
10	20	23	38	23	13	12	85	4	5
11	10	12	24	17	11	11	63	4	5
12	10	12	14	7	1	1	23	4	10
13	20	23	28	13	3	2	45	4	10

Table 3. Freshwater Input of Simulation #2 (Unit: cfs)

RunSeries	LainhartDam	LOXTnpk	CypressCrk	HobeGrv	KitchenCrk	NWFTotal	NF	S46
1	200	279	7	2	1	289	4	500
2	200	279	7	2	1	289	4	5
3	150	209	7	2	1	219	4	5
4	100	140	7	2	1	150	4	5
5	85	119	7	2	1	129	4	5
6	65	91	7	2	1	101	4	5
7	50	70	7	2	1	80	4	5
8	40	56	7	2	1	66	4	5
9	30	42	7	2	1	52	4	5
10	20	28	7	2	1	38	4	5
11	10	14	7	2	1	24	4	5
12	10	14	7	2	1	24	4	10
13	20	28	7	2	1	38	4	10

Results of Simulation #1 and #2

The output of the 11 model runs in each simulation scenario were analyzed to find the "average high tide salinity" and the "average low tide salinity". The results of Simulation #1 are condensed into two color plates that are attached to this document (Figure 12 - 13). The charts include the flow ~ salinity relationship at 7 sites in the Northwest Fork. On the horizontal axis of these charts, the amount of freshwater input was represented by the flow rate at the Lainhart Dam. Given a flow rate on the horizontal axis and draw a vertical line from that point, the line will intersect the seven curves in the chart. Then the salinity of the seven intersecting points can be read from the vertical axis. These are the predicted salinity for the seven locations in the Northwest Fork Loxahatchee River with the given freshwater discharge.

The flow ~ salinity relationship for one of the sites, Site 8a at River Mile 8.1, are plotted in Figure 8 - 11.

A more detailed discussion on Simulation #1 results can be found in the conclusion section of this document.

3.3 The Influence of Inlet Conveyance and Sea Level Rise on the Salinity Regime

3.3.1 Long shore sediment transport and inlet sedimentation

Historic evidence indicates that the Loxahatchee estuary was periodically closed and opened to the sea (McPherson, Sabanskas and Long, 1982). Due to active long shore sediment transport, the Jupiter Inlet was probably characterized by shifting sandbars through which ran a narrow and unstable channel. When James Henshall visited the area in early 1880s, he observed the "Jupiter River" flowing "eastward, and over Jupiter Bar into the sea". He also described the difficulty of sailing through the inlet, which was "quite narrow" and had "an angle in its channel at the worst possible place" (Henshall, 1884). The aerial photo of the inlet from 1940s shows extensive flood shoals (sandbars that were formed by sands pushed into an inlet by tides) which would have limited the hydraulic conveyance of the inlet and the tidal range in the estuary. Under natural conditions with active sedimentation, the hydraulic conveyance of the inlet would be smaller than the conveyance under dredged conditions.

3.3.2 Sea Level Rise

Extensive analyses of tidal records indicates that global sea level has risen at a rate approximately 2 mm per year for at least the last century or so (Douglas, B. C., 1991, 1992). Based on this estimate, the sea level around 1900 would be about eight inches lower than the present level. A lower sea level means a smaller range of tidal influence in an estuary.

The sea level rise was at an even faster rate prior to 1900. About 15,000 years ago, the shore of the Atlantic Ocean was several miles east and more than 300 feet lower than its present location and altitude at Jupiter Inlet. From about 15,000 to 6,000 years ago, sea level rose at a rate of more than 3 feet per century. Tidal waters began to flood the estuary embayment. Prior to this time, the embayment was probably a flood plain or freshwater marsh (McPherson, Sabanskas and Long, 1982).

The rise of sea level has likely increased the range of tidal influence in the Loxahatchee River. If the sea level rise continues as predicted, it is foreseeable that the tide influence will move further upstream along with the sea level rise.

3.3.3 The Effects of Inlet Deepening and Sea Level Rise

The hydrodynamic/salinity model was applied to a preliminary investigation on the impact of inlet dredging and sea level rise. This section outlines the preliminary results of six model simulations that have been completed. Discharges from North Fork and South Fork were assumed constant in this preliminary investigation.

Freshwater input was kept constant through all the six model simulations, only sea level and inlet depth were changed so that their effects on the position of saltwater wedge could be examined. Table 4 lists boundary conditions of five model simulations. Inlet depth was reduced from current condition to an average depth of 6, 4, and 2 feet subsequently. While the first four simulations were all at current sea level, Simulation 5 was at 1900 sea level, which was 8 inches lower. The sixth model simulation, which is not listed in Table 4, used the boundary condition of Simulation 1 except that sea level was one foot higher. The purpose of this simulation was to estimate the possible effects of future sea level rise.

Table 4. Boundary conditions of model simulations

Boundary Condition	Simulation 1	Simulation 2	Simulation 3	Simulation 4	Simulation 5
Sea level	Present MSL	Present MSL	Present MSL	Present MSL	1900 MSL
Discharge at Lainhart Dam	65 cfs	65 cfs	65 cfs	65 cfs	65 cfs
Total freshwater input to Northwest Fork	188 cfs	188 cfs	188 cfs	188 cfs	188 cfs
Freshwater input to North Fork	4 cfs	4 cfs	4 cfs	4 cfs	4 cfs
Freshwater input to South Fork	5 cfs	5 cfs	5 cfs	5 cfs	5 cfs
Inlet condition	1999 condition*	Average depth 6 feet	Average depth 4 feet	Average depth 2 feet	Average depth 2 feet

* The average depth was approximately 8 - 10 feet

To compare the range of tidal influence with various inlet depths, the location of 2 ppt salinity lines of the model simulations 1 through 4 were plotted in Figure 16. The model output indicates that a shallower inlet would reduce the tidal influence on the river. For example, when the inlet depth is reduced to 4 feet by sedimentation, the 2 ppt line would move close to 1 mile downstream from where it is under the current inlet condition. Therefore dredging of the inlet in the past several decades probably has helped move the salt wedge upstream.

The two green lines in Figure 17 are positions of 2 ppt salinity lines at estimated 1900 sea level and a predicted future sea level. The estimated mean sea level in 1900 is 8 inches lower than the current mean sea level. Comparing the results of Simulations 4 (current sea level) and 5 (1900 sea level), the sea level rise itself in the past century would have moved the salt wedge upstream for nearly 0.5 miles. The green line at the upstream end is predicted position of 2 ppt salinity line with one foot sea level rise from current sea level. If the inlet depth and freshwater inflow remain unchanged, the effect of sea level rise will push saltwater further inland.

3.3.4 Discussion

The position of the salt wedge is the balance point between ocean tides and freshwater flow from inland. While the reduction in freshwater flow could cause saltwater intrusion, the modeling results illustrated that deepened inlet and rising sea level would also push salt wedge further inland. Apparently sea level rise and inlet dredging have significant impacts on the salinity regime in the Loxahatchee Estuary.

A relationship between the freshwater inflow and the position of salt wedge in the Loxahatchee Estuary was described in Section 3.2.2. The analysis was based on the current inlet configuration and sea level. Based on the model simulations with shower inlet and lower sea level, Table 5 lists the amount of freshwater required under the present condition to keep the 2 ppt line at the positions that correspond to the 2ppt line position under the three historic scenarios.

Table 5. Increased freshwater demand to prevent saltwater intrusion

Present and historic conditions	2 ppt line river mile	Required freshwater under historic condition (cfs)		Required freshwater under present condition (cfs)	
		Freshwater discharge at Lainhart Dam	Freshwater input to NWF	Freshwater discharge at Lainhart Dam	Freshwater input to NWF
A-Present condition	8.25			65	188
B-Inlet average depth 6 ft	7.7	65	188	85	246
C-Inlet average depth 4 ft	7.4	65	188	100	289
D-Inlet depth 4 ft, 1900 MSL	7.0	65	188	120	347

While the relationship between sea level rise and salt wedge intrusion may not be linear, a rough estimate can be made based on the modeling results. According to Table 2, the freshwater required to overcome the effects of sea level rise over the last 100 years is about 20 cfs. If the sea level rise continues at the same rate, the freshwater demand will increase at a rate of 0.2 cfs per year at Lainhart Dam and 0.6 cfs per year for the Northwest Fork.

3.3.5 Summary

The analysis outlined above indicates that sea level rise and inlet dredging have significant impacts on the salinity regime in the Loxahatchee Estuary. Due to the changes in sea level and inlet configuration, the demand for freshwater has increased to prevent salt water intrusion.

Inlet sedimentation is a very dynamic process. The modeling effort outlined in this document is just the first step of a preliminary investigation. More efforts are necessary to acquire historic bathymetry and sea level data and improve the accuracy of model simulation.

3.4 Modeling Historic Salinity Conditions in the Northwest Fork from 1971 to 2000

3.4.1 Methodology

Based on the simulation with various freshwater inflows, a flow/salinity relationship was established for locations in the Northwest Fork Loxahatchee River. The salinity in the following table is the average of high and low tide salinity that were presented in the previous sections.

Table 6. Estimated daily mean salinity in Northwest Fork vs. flow at Lainhart Dam

	Station ID							
Flow(cfs)	10B	9C	66	9B	8st	65	8B	64
200	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.2
150	0.1	0.1	0.1	0.1	0.1	0.2	0.2	0.4
100	0.1	0.1	0.1	0.1	0.2	0.3	0.5	1.5
85	0.1	0.1	0.1	0.2	0.3	0.5	0.9	2.3
65	0.1	0.2	0.2	0.3	0.7	1.3	1.9	4.2
50	0.1	0.3	0.5	0.8	1.3	2.3	3.3	6.2
40	0.2	0.6	0.9	1.4	2.2	3.5	4.7	8.0
30	0.3	1.2	1.8	2.5	3.6	5.3	6.7	10.4
20	0.8	2.3	3.3	4.2	5.6	7.7	9.3	13.1
10	2.0	4.7	5.9	7.2	8.8	11.2	12.8	16.6

While the salinity level in the table is based on an equilibrium state with steady freshwater inflow, in reality freshwater inflow rarely is constant. The salinity condition observed in the estuary is the results of a series of transitions from one state to the next. Therefore the change in salinity always lags behind the flow change. Following is a graphic description of salinity transition. The dotted line indicates the equilibrium salinity. Following an increase of freshwater inflow, salinity in the estuary will decrease accordingly and approach gradually to a new equilibrium state.

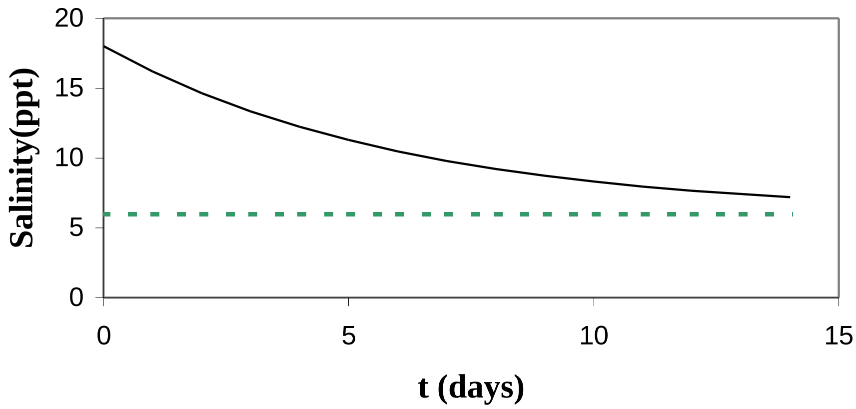

Chart 7. Salinity regime transition process

Both field observation and model simulation indicate that the salinity condition in the estuary is consisted of a series of transitions from one quasi-equilibrium condition to another. A computer program was written based on this concept. Both field data and model output were analyzed to establish the transition time and freshwater inflow/salinity relationship for stations in the estuary. The computer program firstly calculates the potential target (equilibrium) salinity based on the magnitude of freshwater inflow. Then it calculates the salinity change on daily time steps. This calculation would consider both target salinity and the initial salinity condition at the beginning of the time step. If there is further freshwater inflow change before the transition is completed, then a new transition begins and the program repeats the same computational procedure for the new transition. Since the computer program was designed for long term salinity calculations, it will be referred to as "long-term model" in the subsequent sections.

Figure 19 through 21 are the testing output of the long-term model. The output was compared with real data at three salinity stations in the Northwest Fork. Since the model operates on daily time steps, the model output is daily averaged value that does not depict the daily variation between two high and two low tides. The model was developed based on mean salinity over two spring-neap tidal cycles, it does not reflect the tidal regime difference between spring and neap tides.

3.4.2 Long-term model applications

The long-term model was applied to provide a hind cast of the salinity conditions at eight sites in the Northwest Fork for the period from 1970 to 2001. Figure 22 and 23 are the long term model outputs for Station 64 and 65. The results were used by biologists in the study team to investigate the effects of salinity on the biological characteristics of the upper Northwest Fork.

4. Discussion

The 2-D hydrodynamic/salinity model was able to follow the general trend of salinity changes that was observed in the system. This seems to confirm that the freshwater inflow rate at Lainhart Dam can be used as an surrogate indicator of total freshwater input to the estuary. On the other hand, the lack of flow data from several major tributaries has been a limiting factor in model calibration and applications.

Groundwater input is a major factor in the salinity balance of the system, especially under dry conditions. The groundwater input to the system is affected by groundwater table and river stage. The constant groundwater input assumption used in this study is just the first step in bringing groundwater into consideration. When the preliminary model results are applied to conditions where groundwater input could be less during an extended drought or more after a rainy season, the chart reading should be adjusted accordingly.

Precipitation and evaporation are not simulated in the current model. Precipitation and evaporation should be included in the model at the next step to improve the model accuracy.

The model results have been highly summarized in this document. The dynamic nature of the system response is not fully reflected in the charts that are presented. The original model output contains a huge amount of information that describes the dynamic process in the system.

When new information on freshwater inflow, groundwater input, continuous tide record, precipitation and evaporation becomes available, the model can be improved to provide more accurate results.

The modeling results described in this document are concentrated in the Northwest Fork. Since the model mesh covers the entire estuary it can be potentially applied to studies in other areas, including middle and lower estuary and the inlet, within the model mesh.

5. Conclusions

The Loxahatchee Estuary Salinity Model was developed using field data that had been acquired since the previous major salinity modeling effort for Loxahatchee Estuary. Compared to the USGS model developed in early 80s, the current model was able to cover the upstream portion of the Northwest Fork where the Loxahatchee River District has established long-term salinity records. The model output is consistent with the results of field measurements and indicates a clear correlation between salinity condition and freshwater inflow rate. The relationship described in this document, when combined with the results of biological studies, could provide a scientific basis for system management decision making.

Both field data analysis and the model output indicate a strong correlation between the amount of freshwater input and the estuarine salinity regime. The upstream portion of Northwest Fork is especially sensitive to changes in the freshwater input. Both the field data and model results indicate that a change of freshwater input as small as 10 cfs can cause detectable salinity changes in the area.

To facilitate the management decision making process, maps of 2-ppt salinity lines were prepared based on model output (Figure 14 and 15). Figure 14 shows the spatial positions of 2-ppt salinity lines with various freshwater inflow rates at high tide. Figure 15 shows the 2-ppt lines at low tide. The maps are summaries of a series of 9 model simulations with various freshwater inflow rates. Since the salt wedge is closely associated with 2-ppt salinity line, these two maps illustrate the relationship between salt wedge position and freshwater inflow rate. Salt wedge moves following tides. Therefore maps were developed at both high and low tides.

The difference between spring and neap tides is also a significant factor. To present the 2-ppt lines under an average tide condition, the results in Figure 14 and 15 were taken at a tide range of 2.48 ft at Jupiter Inlet. The mean tidal range there is 2.46 ft according to NOAA data. Therefore the results presented on the maps are under an "average tidal condition". The 2-ppt lines shown in these maps will be at about the middle point between the position of salt wedge at spring tides and that at the neap tides.

2-ppt salinity line locations can also be interpreted from charts in Figure 12 and 13. Table 7 is based on flow ~ salinity relationship presented in Figure 12. The table listed the flow rate of freshwater input that is required to maintain salinity below 2-ppt at various locations in the Northwest Fork.

Table 7. Freshwater inflow required to maintain high tide salinity below 2ppt at seven locations in the Northwest Fork

River Mile	Station #	Freshwater discharge into Northwest Fork above Kitching Creek (cfs)*	Estimated discharge at Lainhart Dam(cfs)
6.5	#63	424	187
7.5	7B	291	128
7.7	#64	202	89
8.1	8A	168	74
8.6	#65	123	54
8.9	8st	95	42
9.4	#66	64	28

*Assume an additional 40-cfs from groundwater that is not included in this number.

Charts in Figure 12 and 13 were based on "average high tide salinity" or "average low tide salinity". Compared to the maps in Figure 14 and 15, the freshwater inflow rate subtracted from the charts in Figure 12 or 13 will tend to be conservative requiring a slightly higher freshwater inflow.

The two-dimensional hydrodynamic/salinity model simulations indicates the hydraulic conveyance of the inlet and sea level rise have significant impact on the salinity regime in the estuary. In addition to freshwater inflow, the effects of inlet deepening and sea level rise need to be considered in system management.

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Preliminary Results of Loxahatchee Estuary Hydrodynamics/Salinity Model

Figures

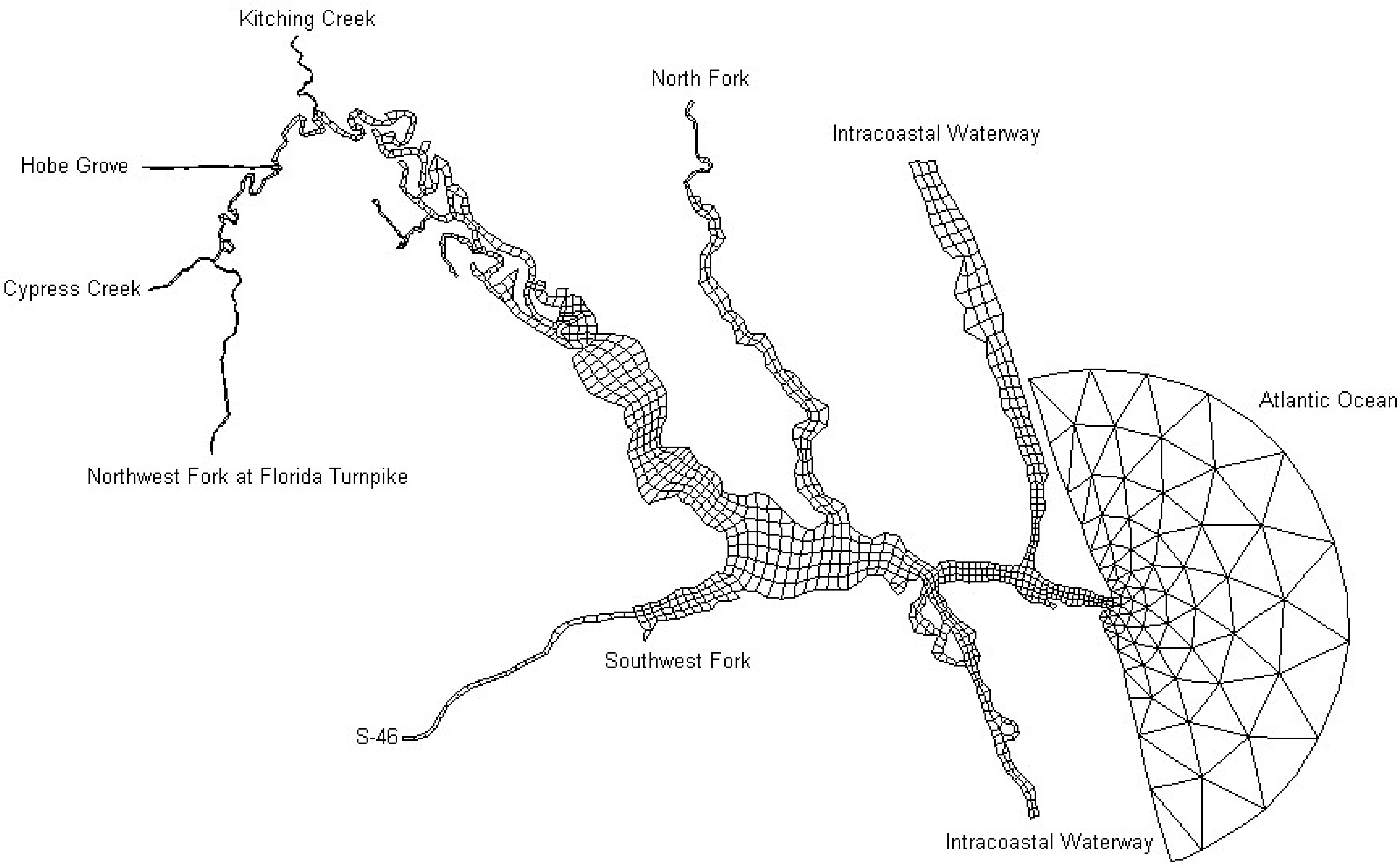


Figure 1. Finite element mesh of Loxahatchee Estuary Salinity Model

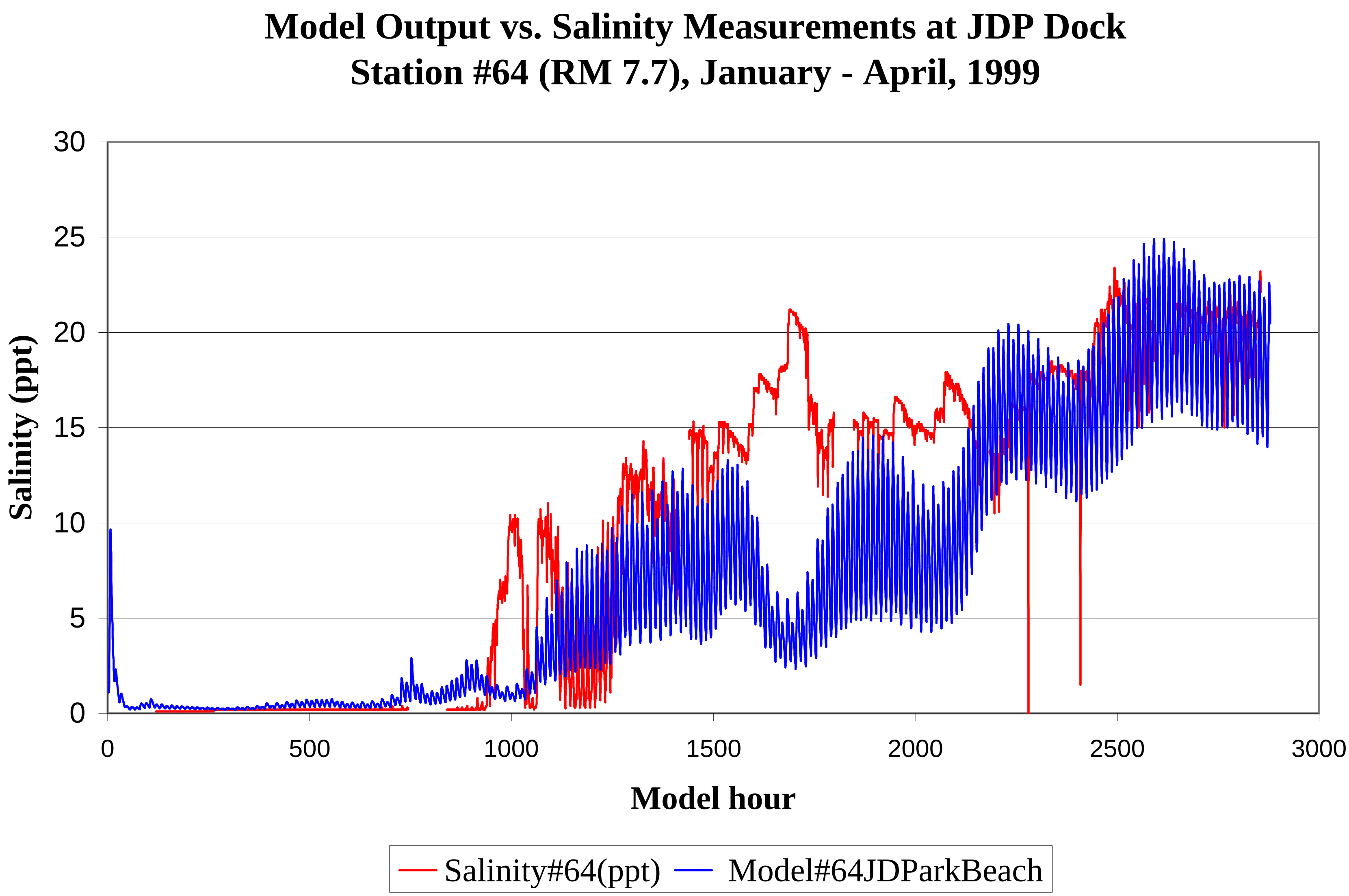


Figure 2. Comparison of model output and field record at Station 64 (RM 7.7)

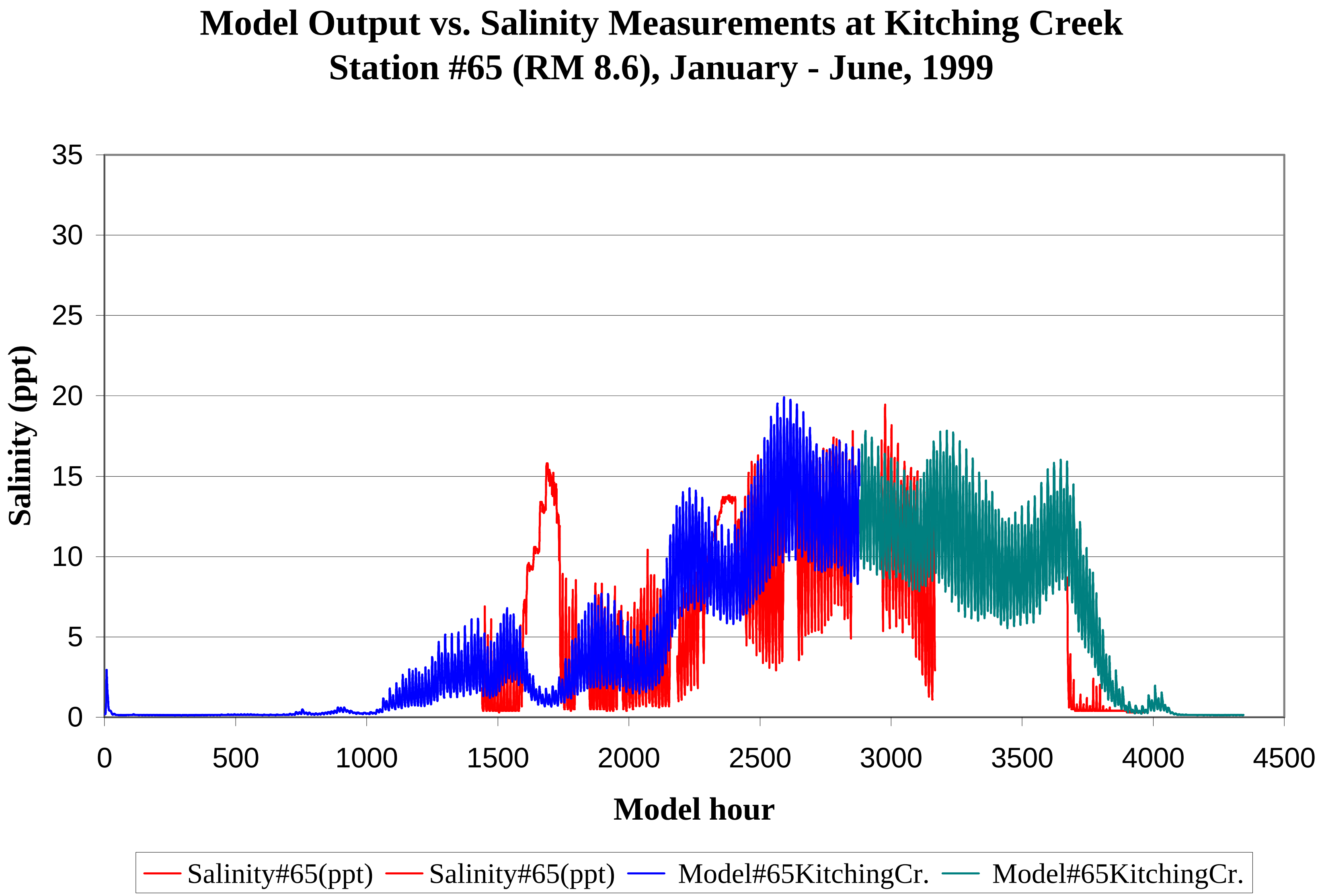


Figure 3. Comparison of model output and field record at Station 65 (RM 8.6)

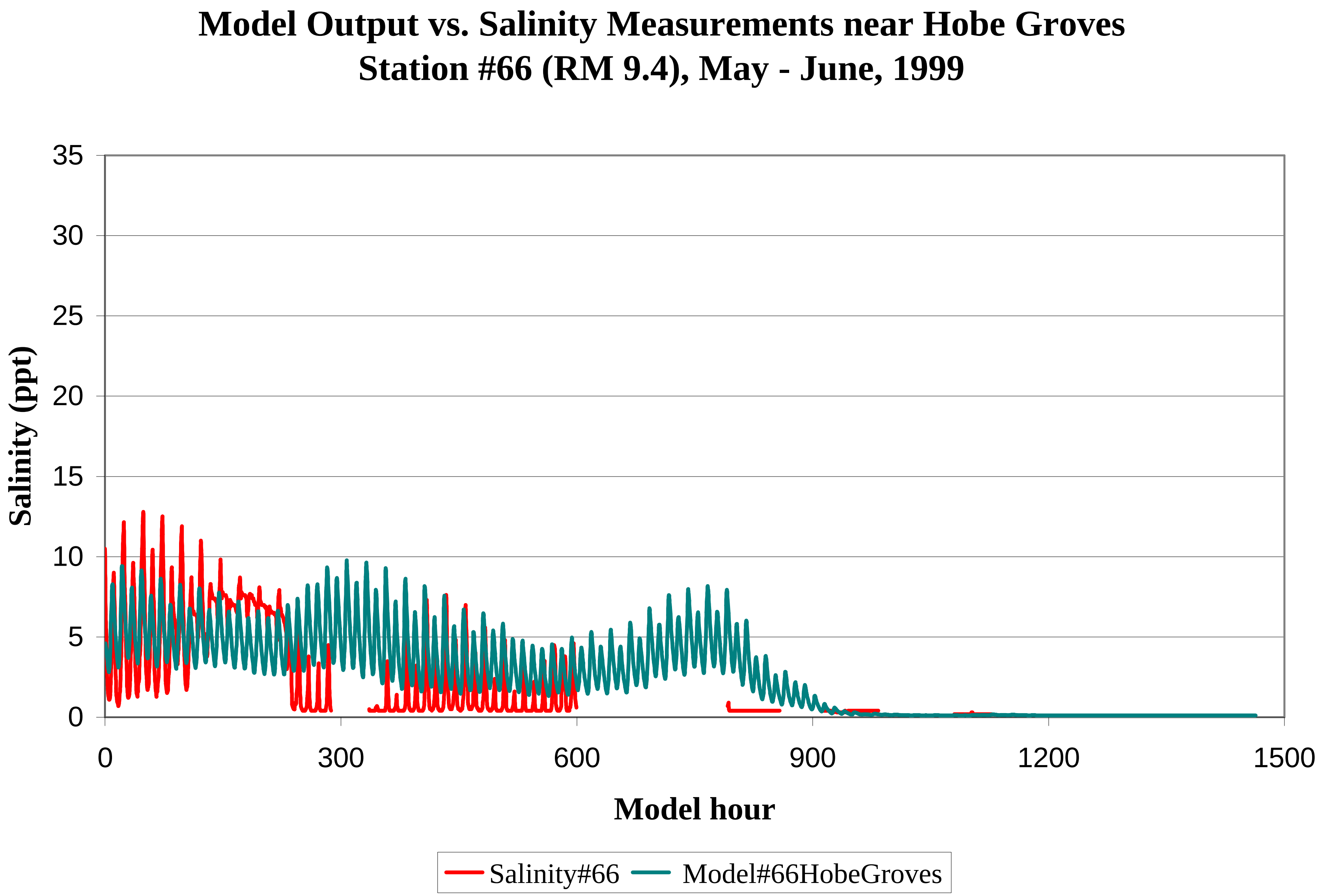


Figure 4. Comparison of model output and field record at Station 66 (RM 9.4)

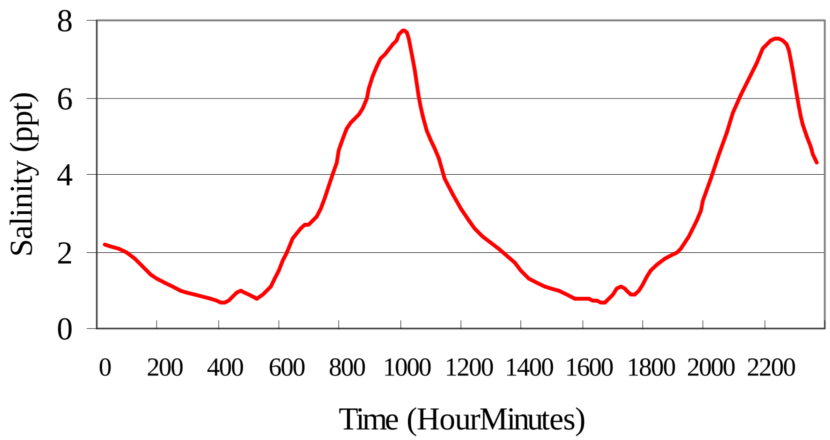


Figure 5. Semidiurnal salinity fluctuation at Station 66 (RM 8.6), March 31, 1999

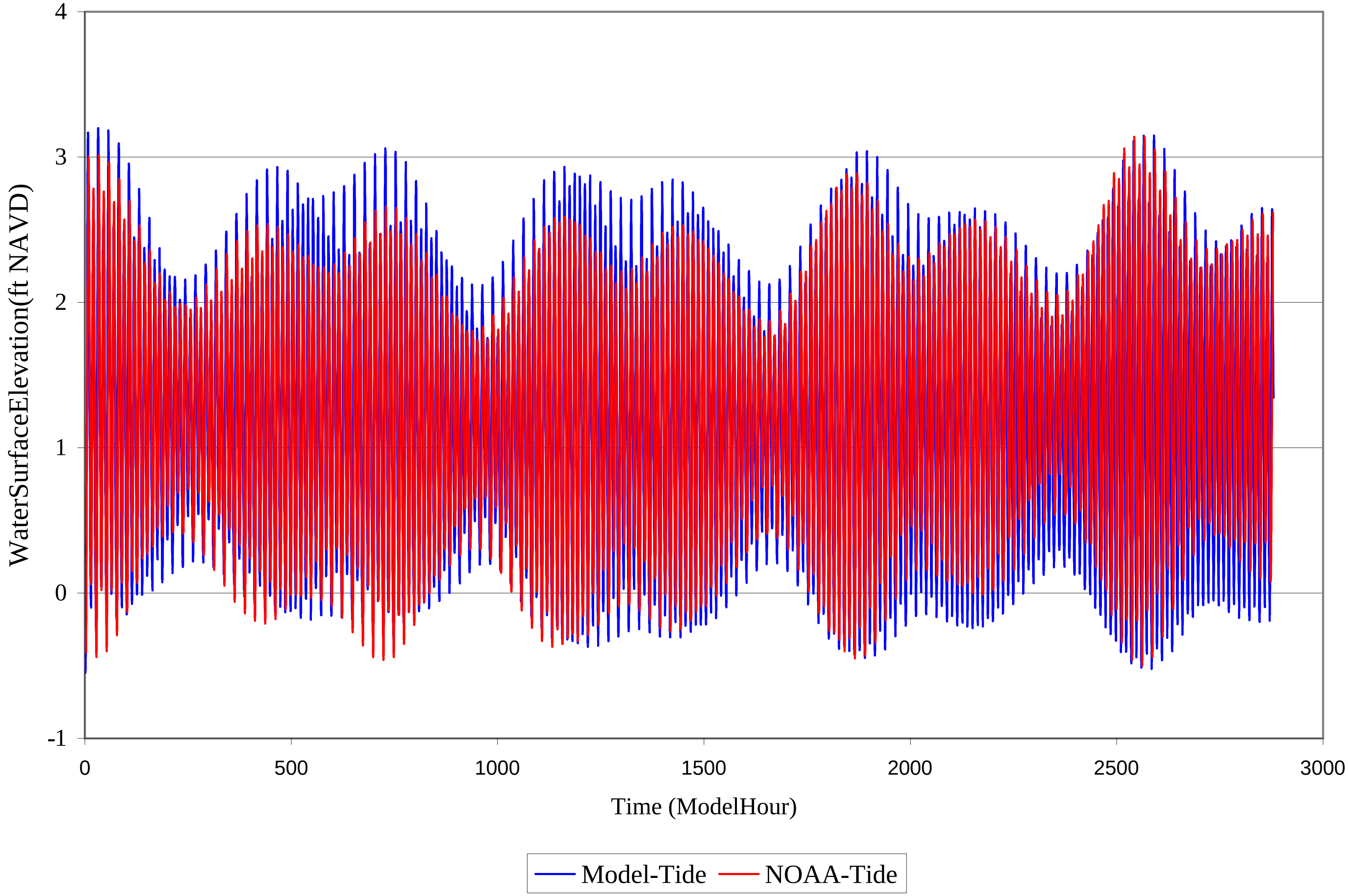
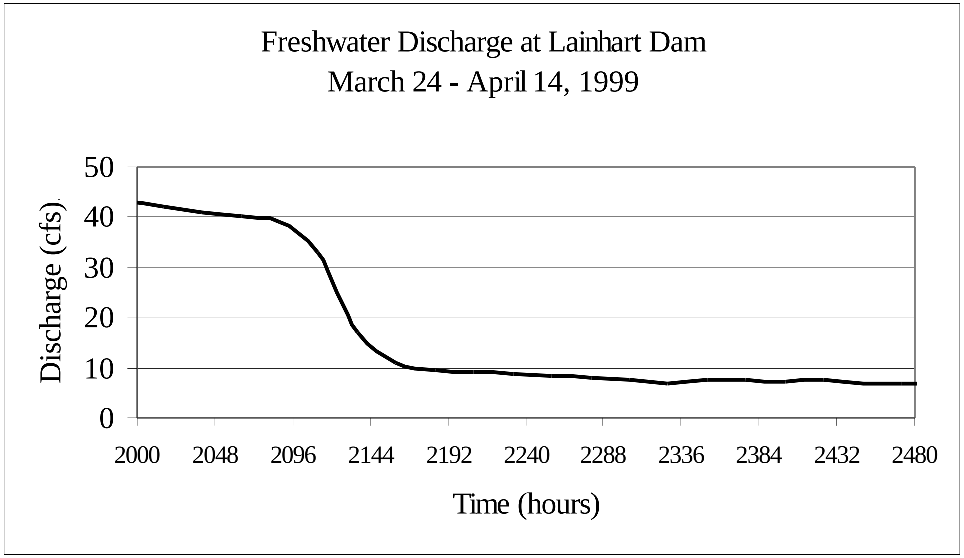


Figure 6. Model output vs. NOAA data: Tides at BoyScoutDock, January 1 - April 30, 1999



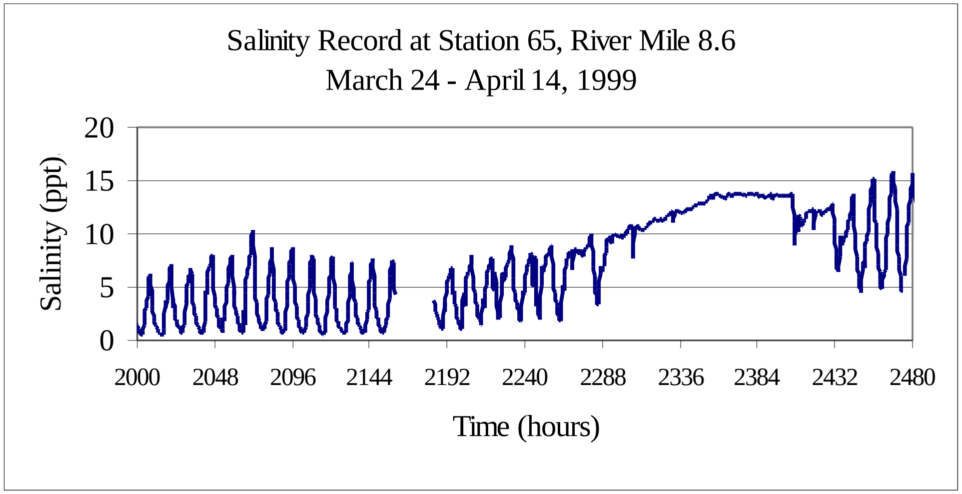


Figure 7a. Transition of salinity regime in response to freshwater input decrease

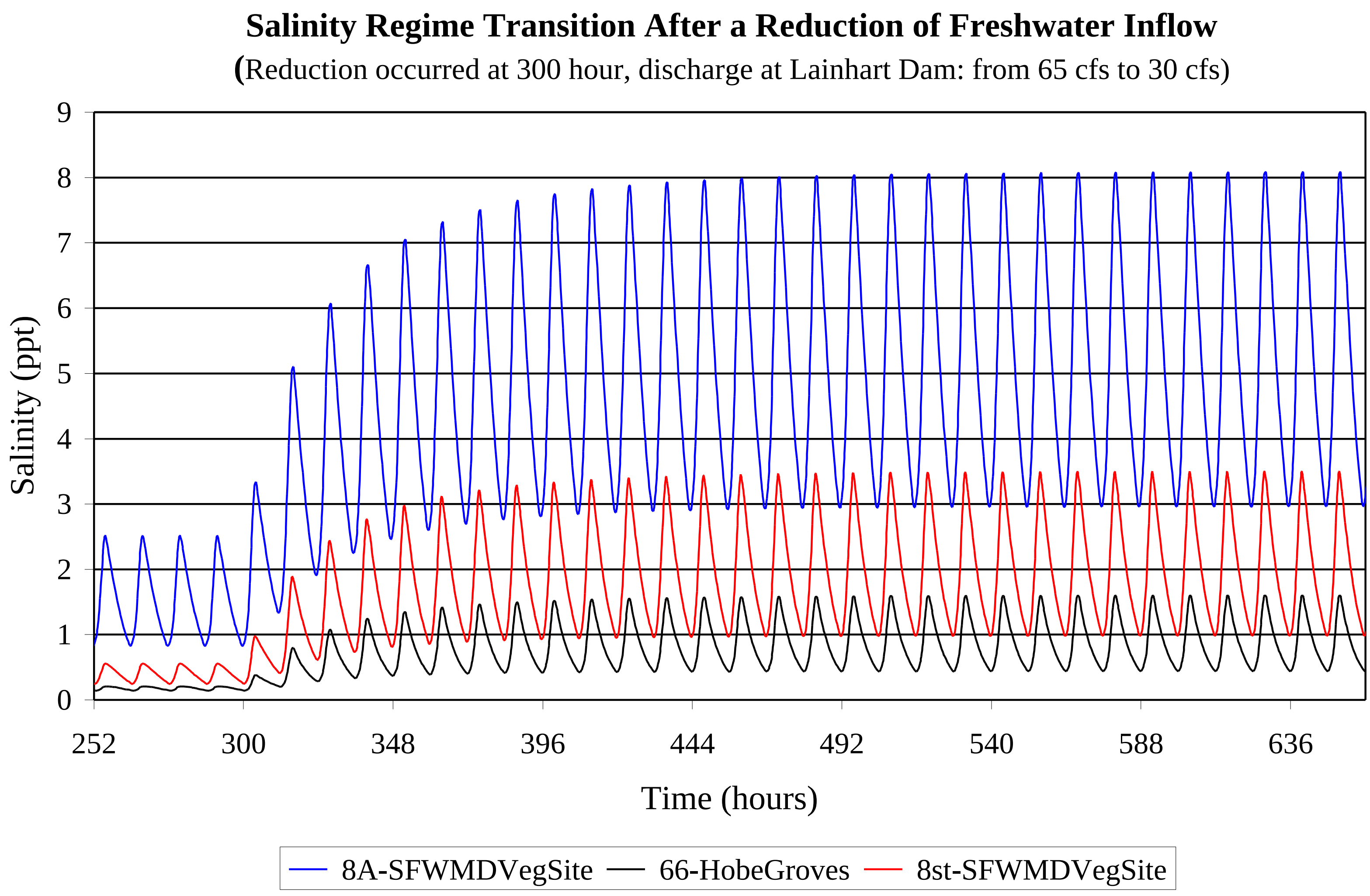


Figure 7b. Transition of salinity regime in response to freshwater input change (Model simulation)

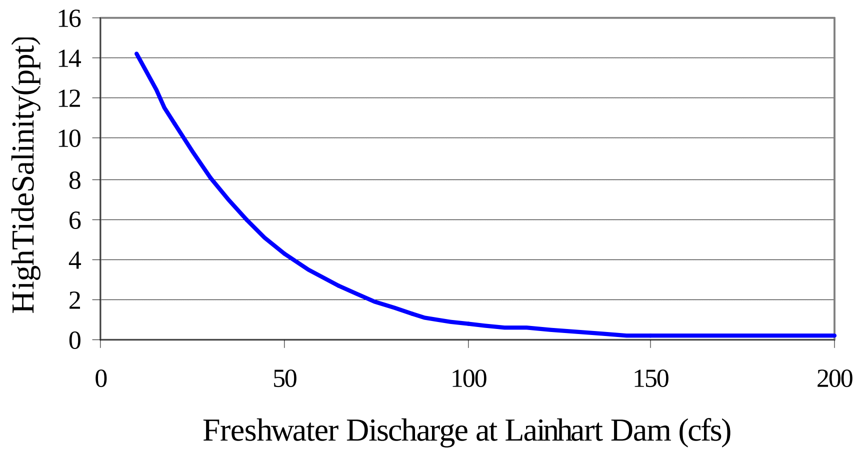


Figure 8. Results of Simulation #1: High tide salinity at Station 8a (RM 8.1)

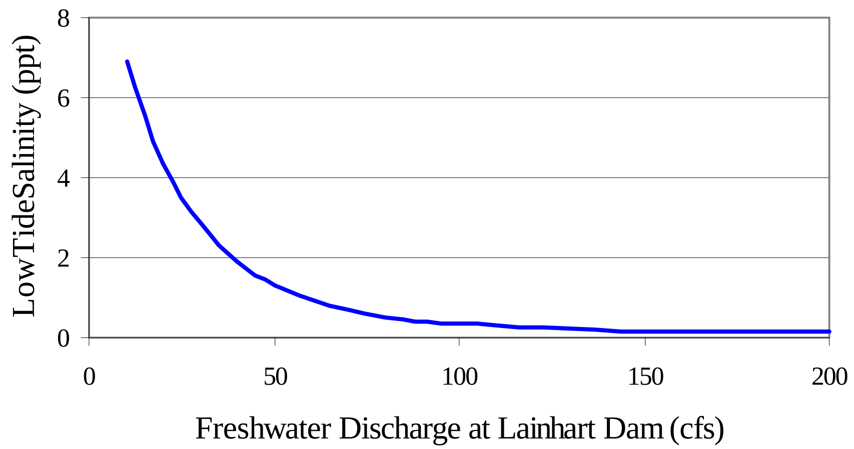


Figure 9. Results of Simulation #1: Low tide salinity at Station 8a (RM 8.1)

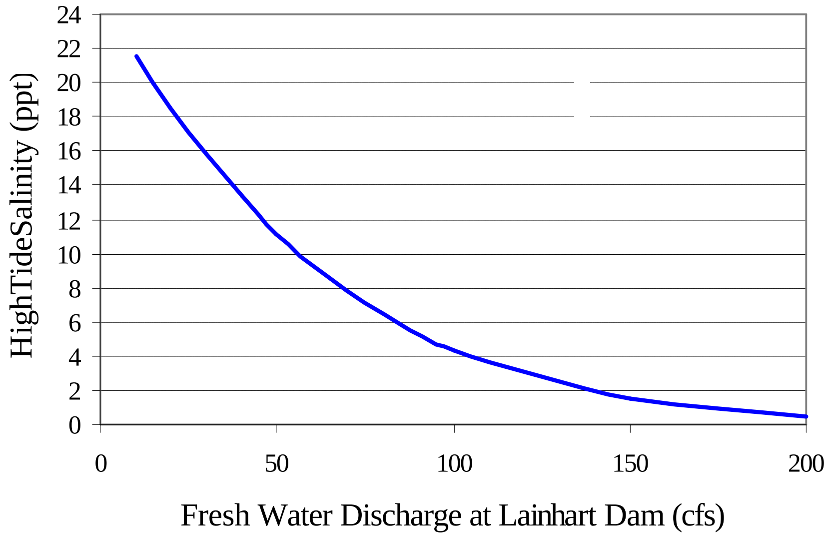


Figure 10. Results of Simulation #2: High tide salinity at Station 8a (RM 8.1)
(Worst case, low flow scenario)

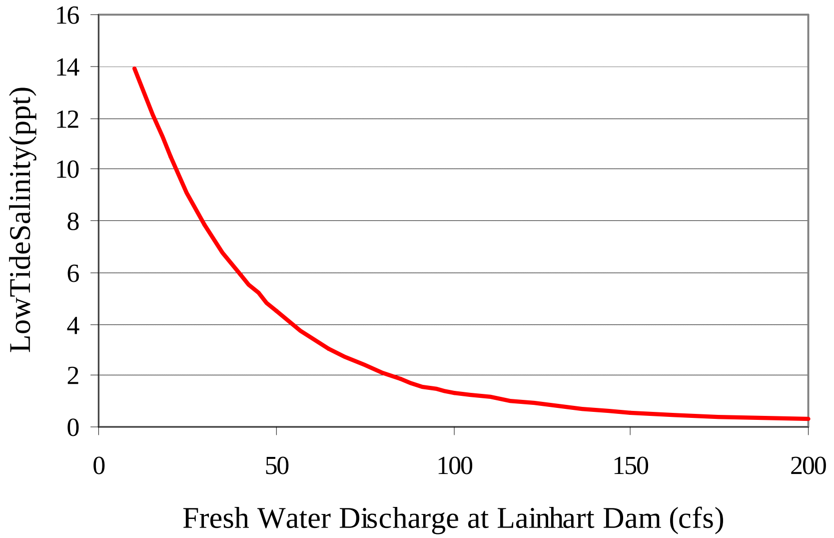


Figure 11. Results of Simulation #2: Low tide salinity at Station 8a (RM 8.1) (Worst case, low flow scenario)

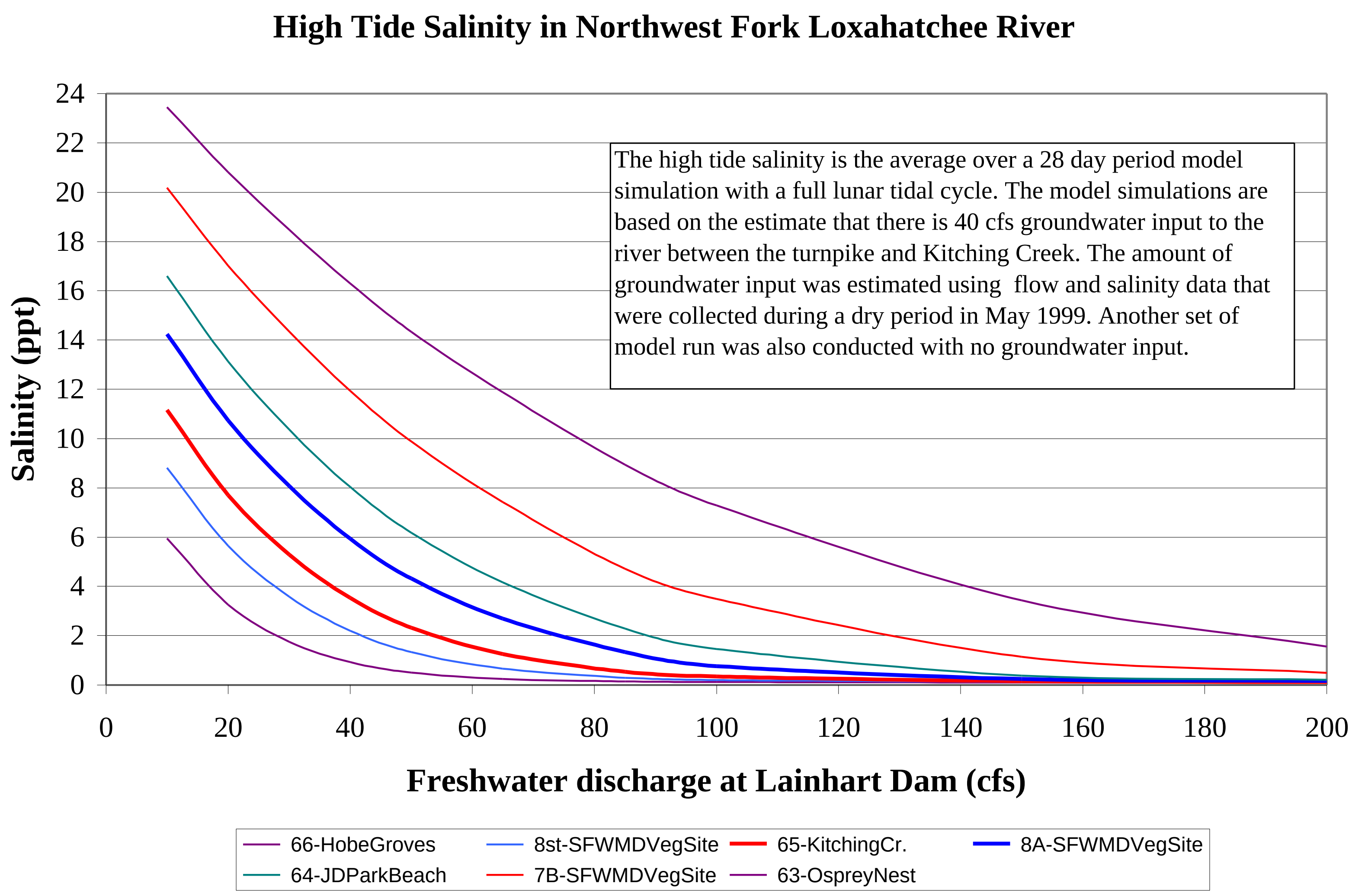


Figure 12. The relationship between high tide salinity and the amount of freshwater inflow

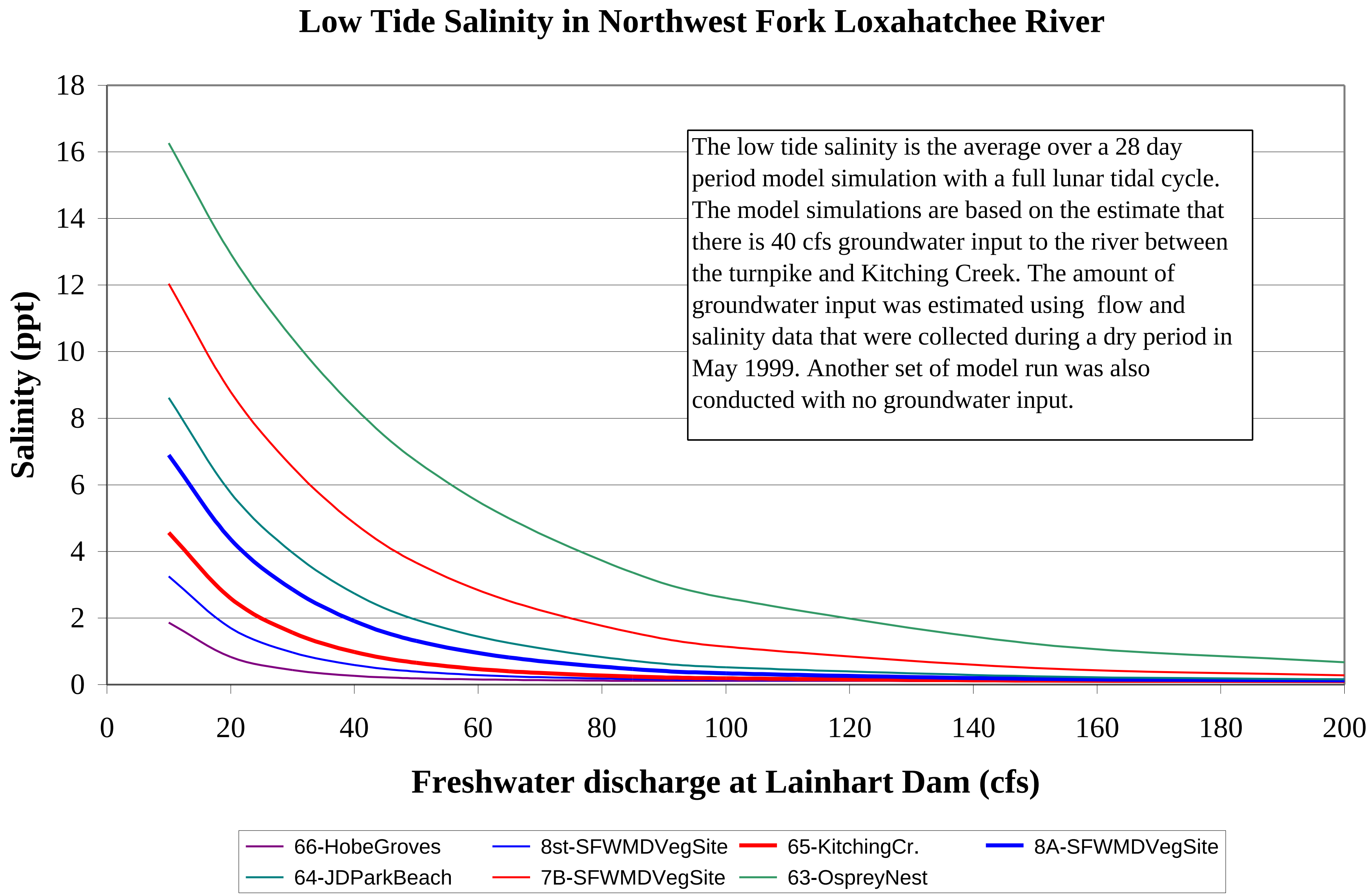


Figure 13. The relationship between low tide salinity and the amount of freshwater inflow

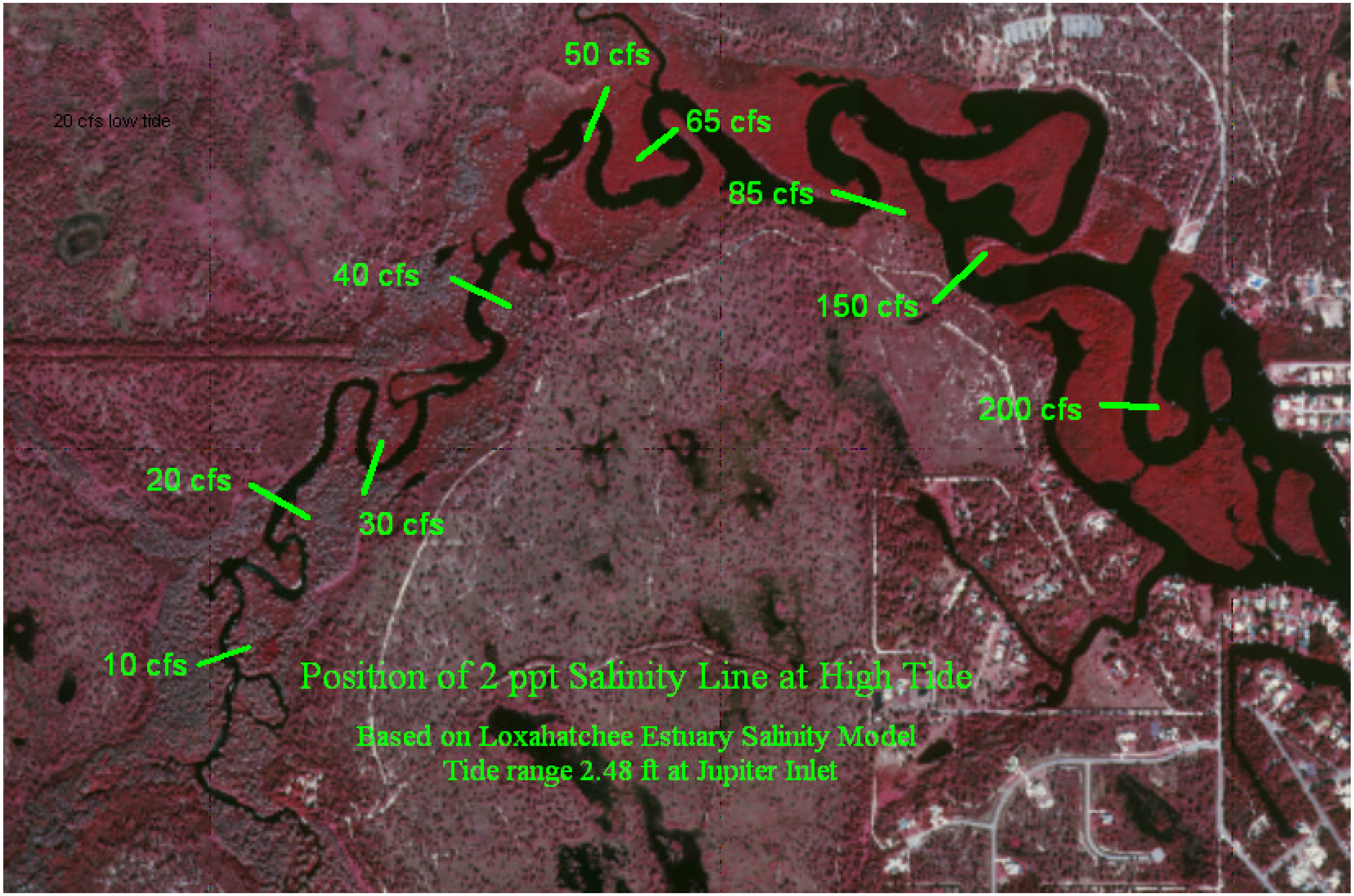


Figure 14. 2-ppt salinity line position at high tide
2-ppt lines are labeled with discharge at Lainhart Dam

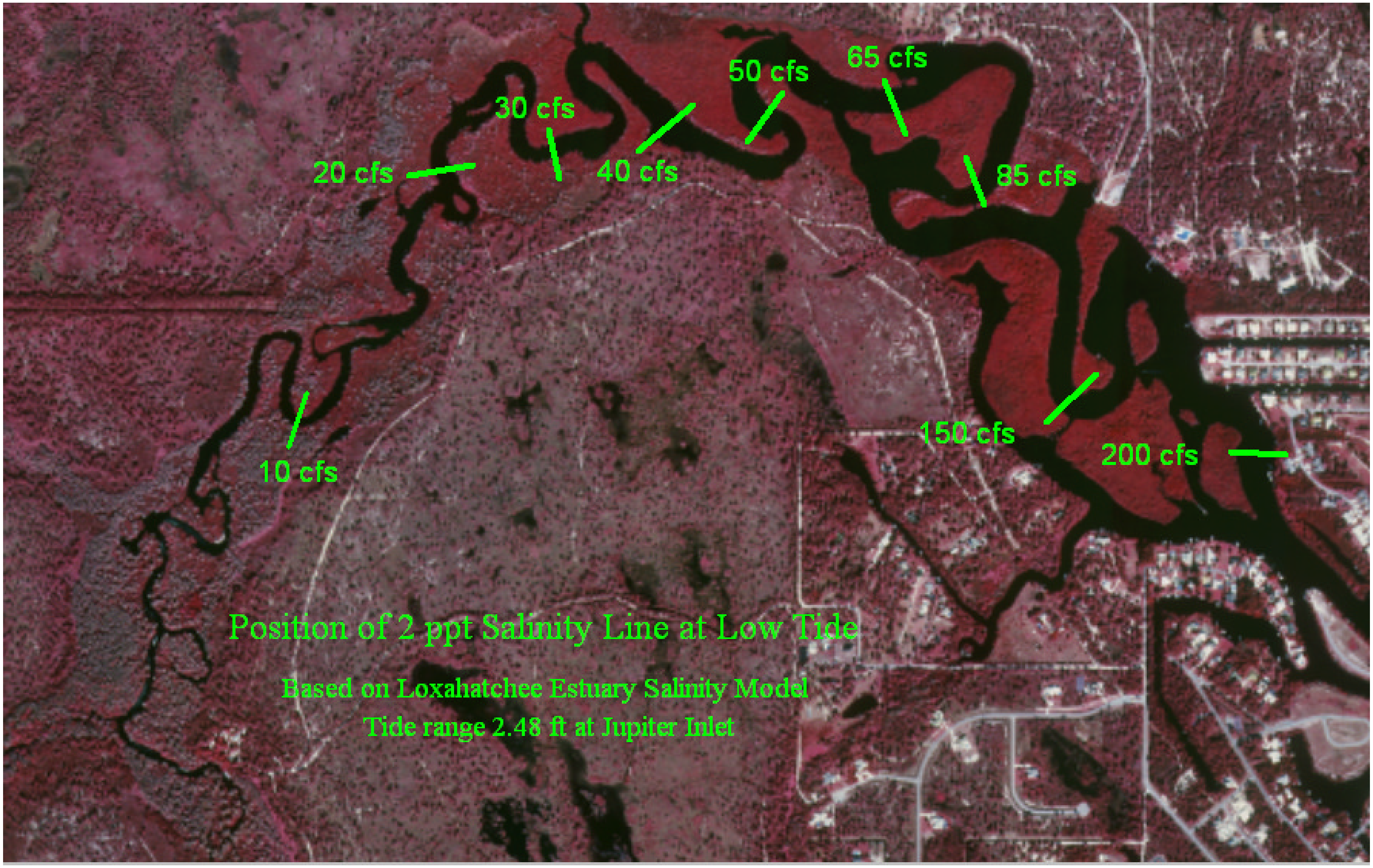


Figure 15. 2-ppt salinity line position at low tide.
2-ppt lines are labeled with discharge at Lainhart Dam

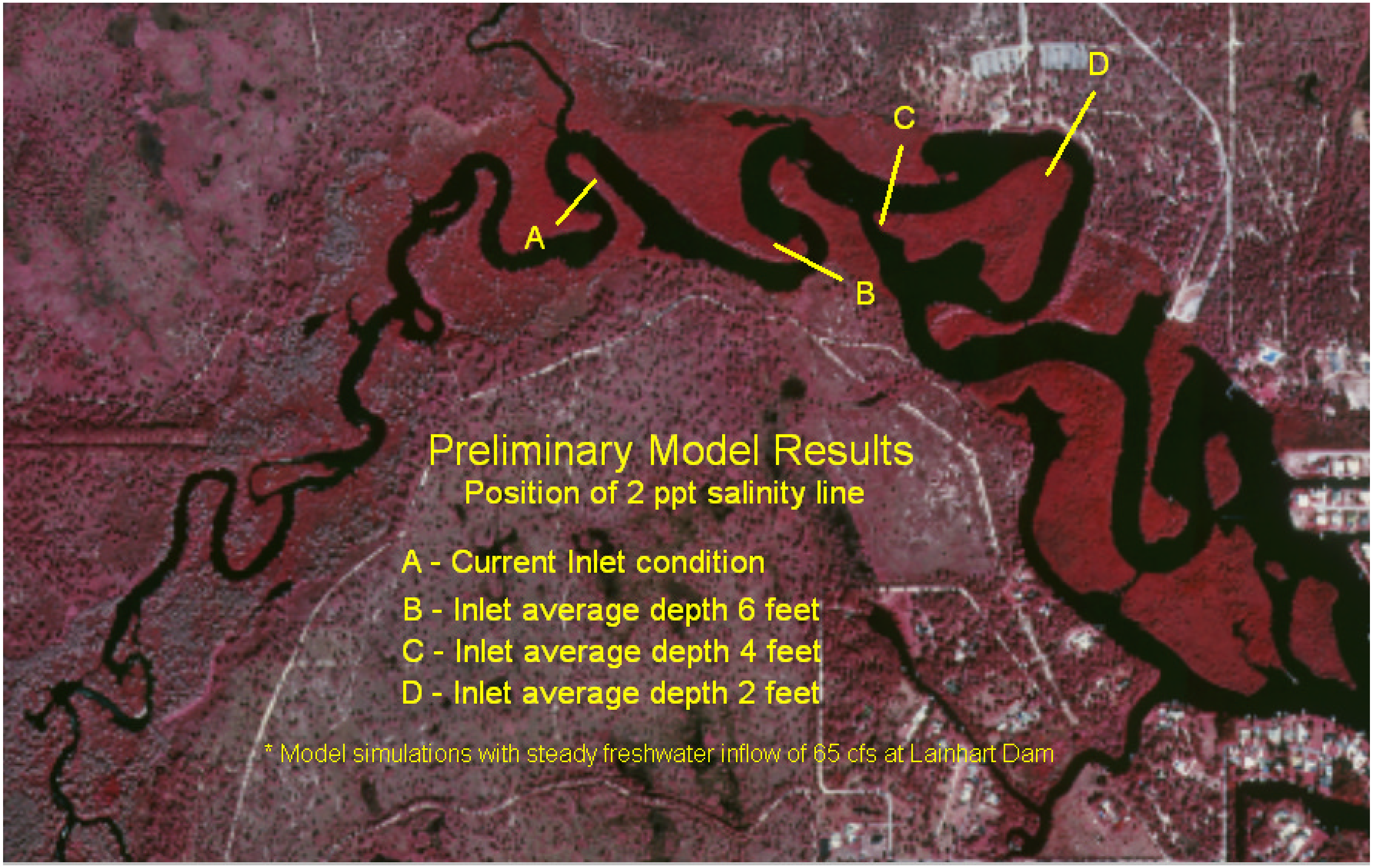


Figure 16. 2-ppt salinity line position at various inlet depths.
2-ppt lines are labeled with depth at Jupiter Inlet

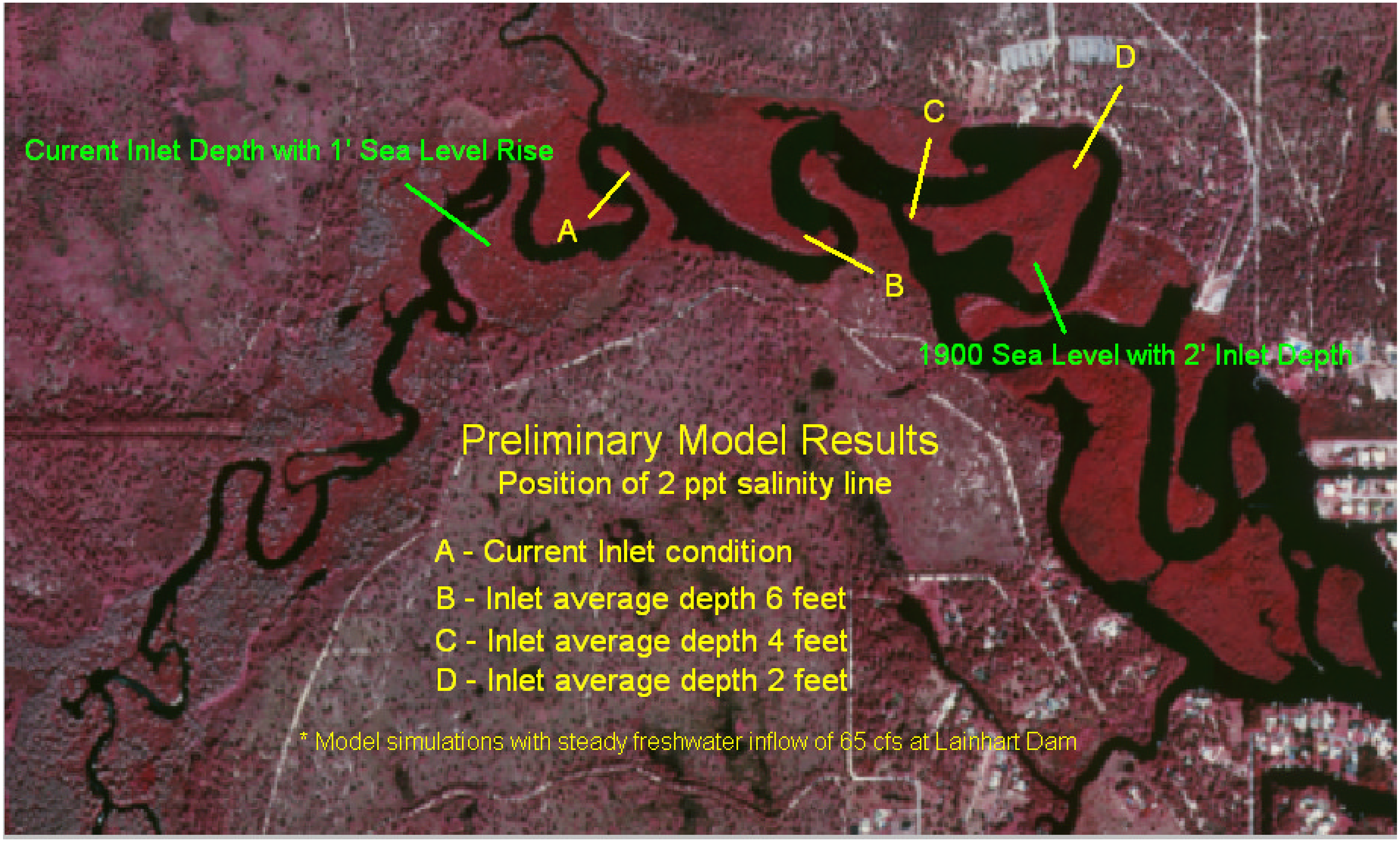


Figure 17. 2-ppt salinity line position at various inlet depths and sea level.
2-ppt lines are labeled with depth at Jupiter Inlet and sea level

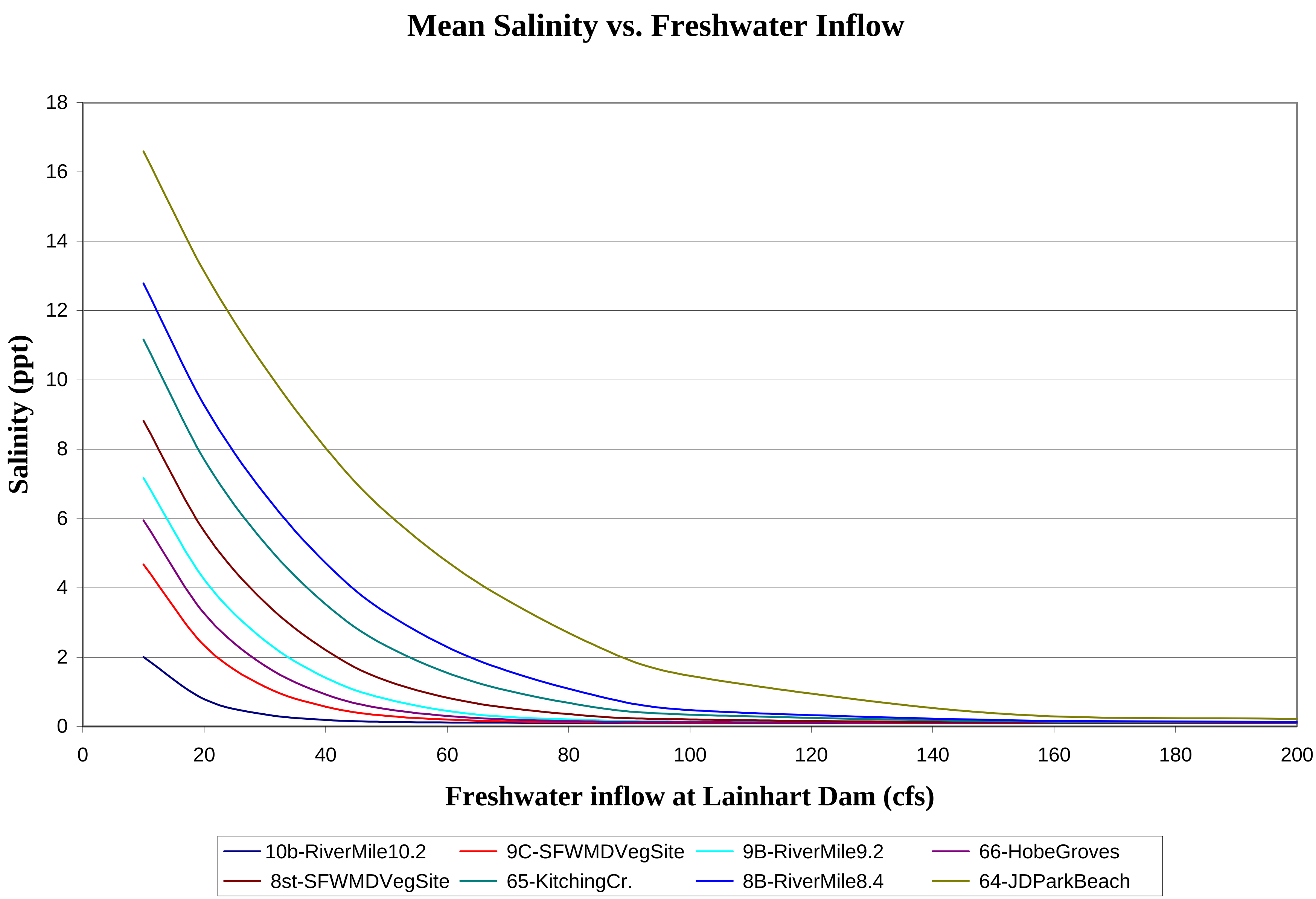


Figure 18. The relationship between mean salinity and the amount of freshwater inflow

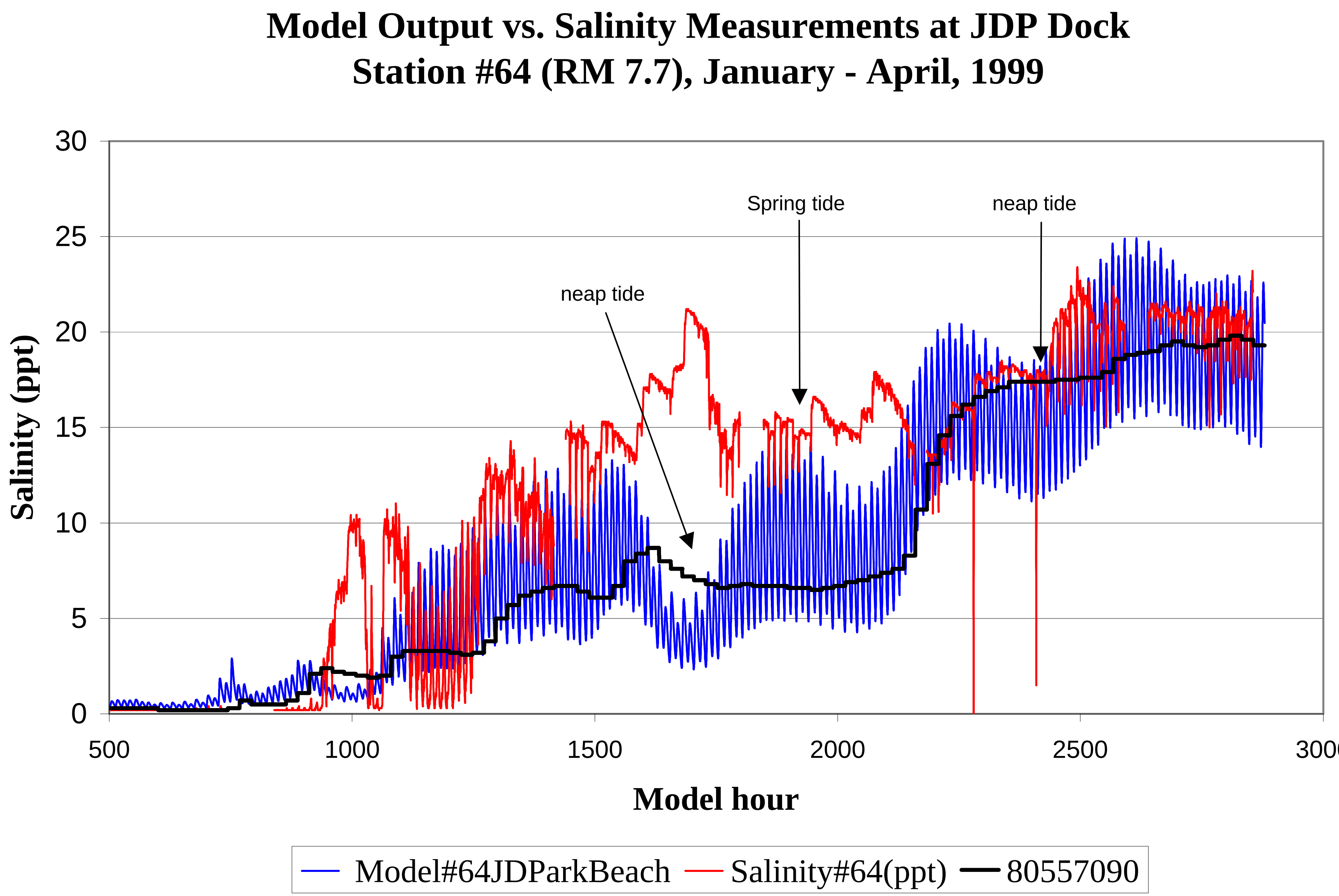


Figure 19. The long term model verification – Site 64

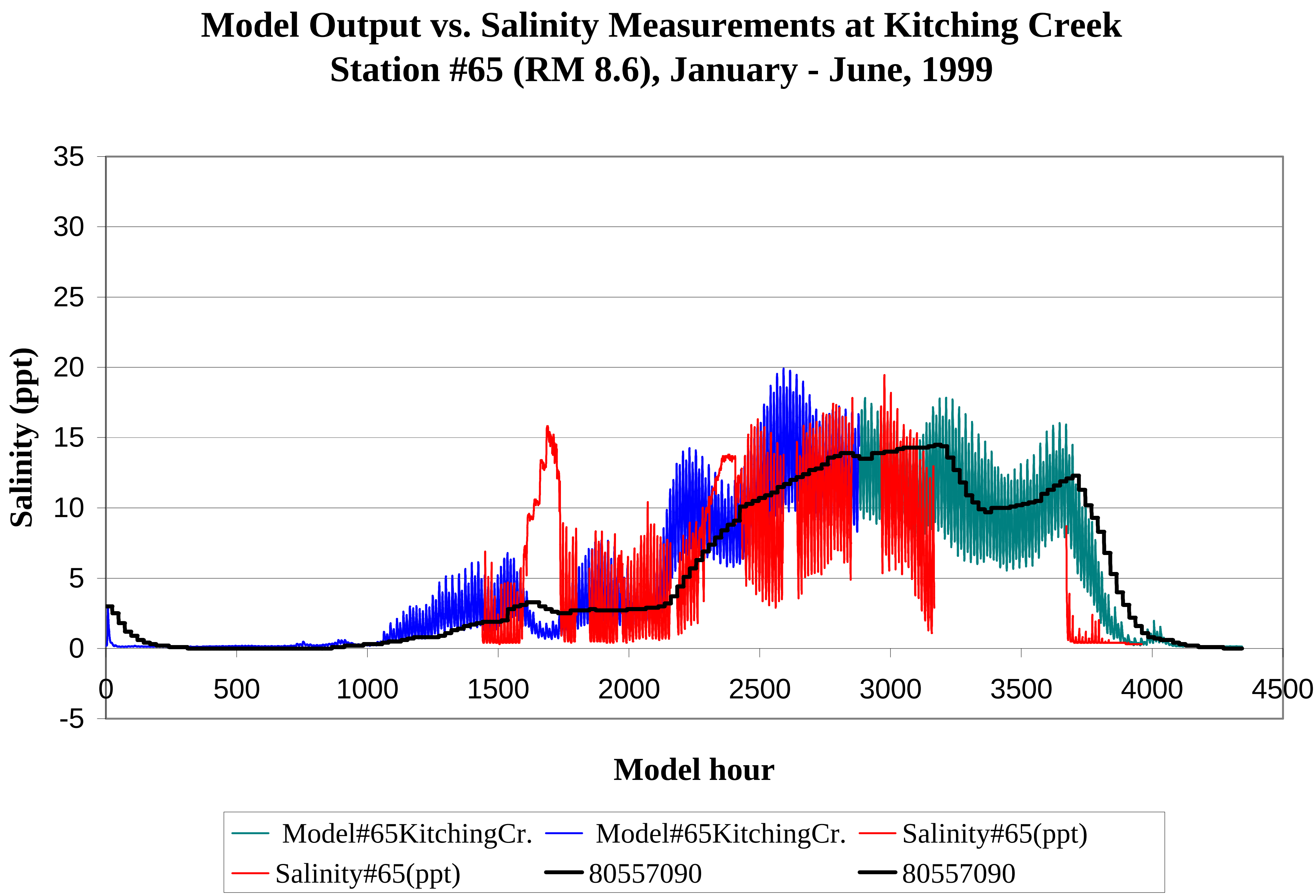


Figure 20. The long term model verification – Site 65

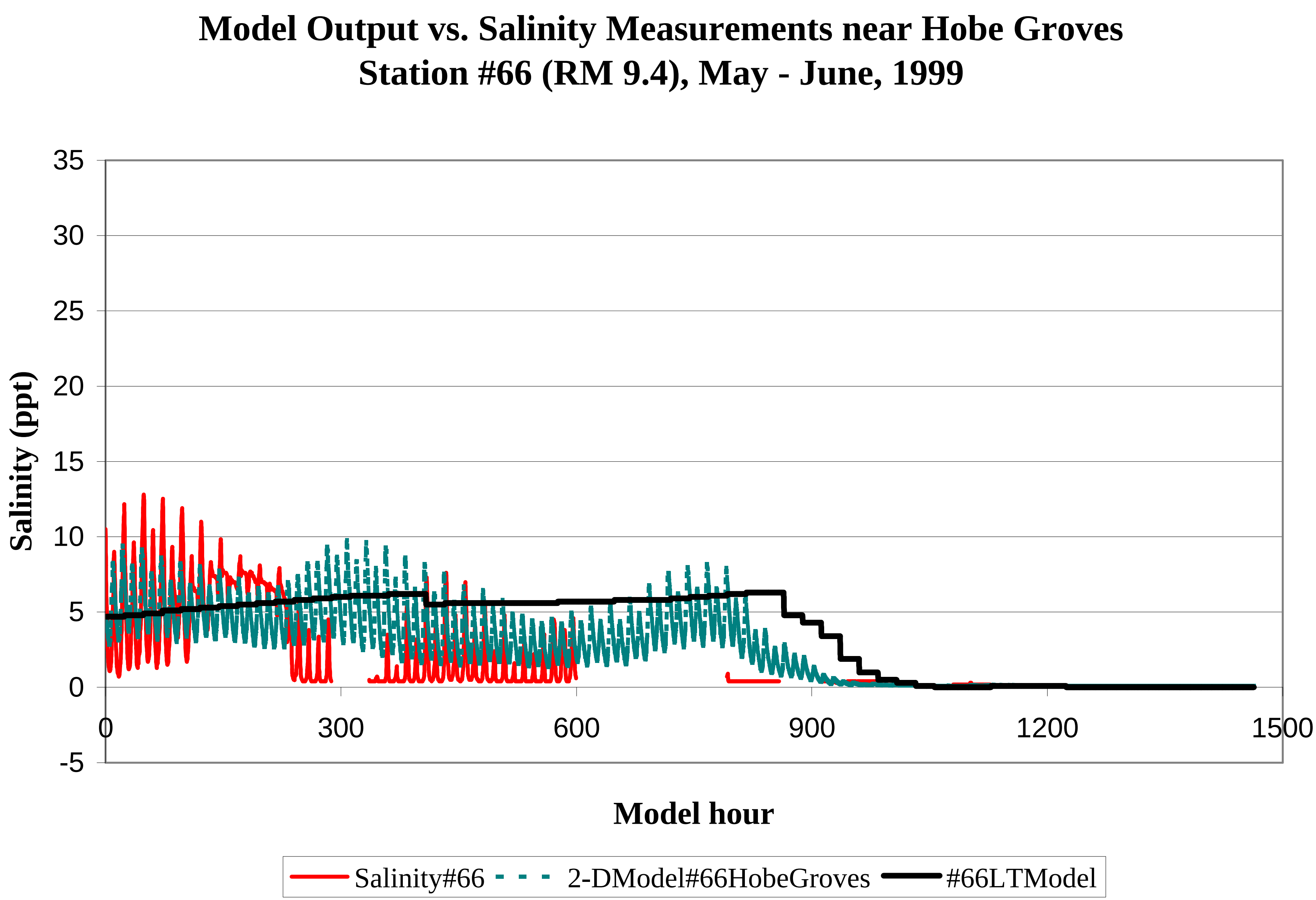


Figure 21. The long term model verification – Site 66

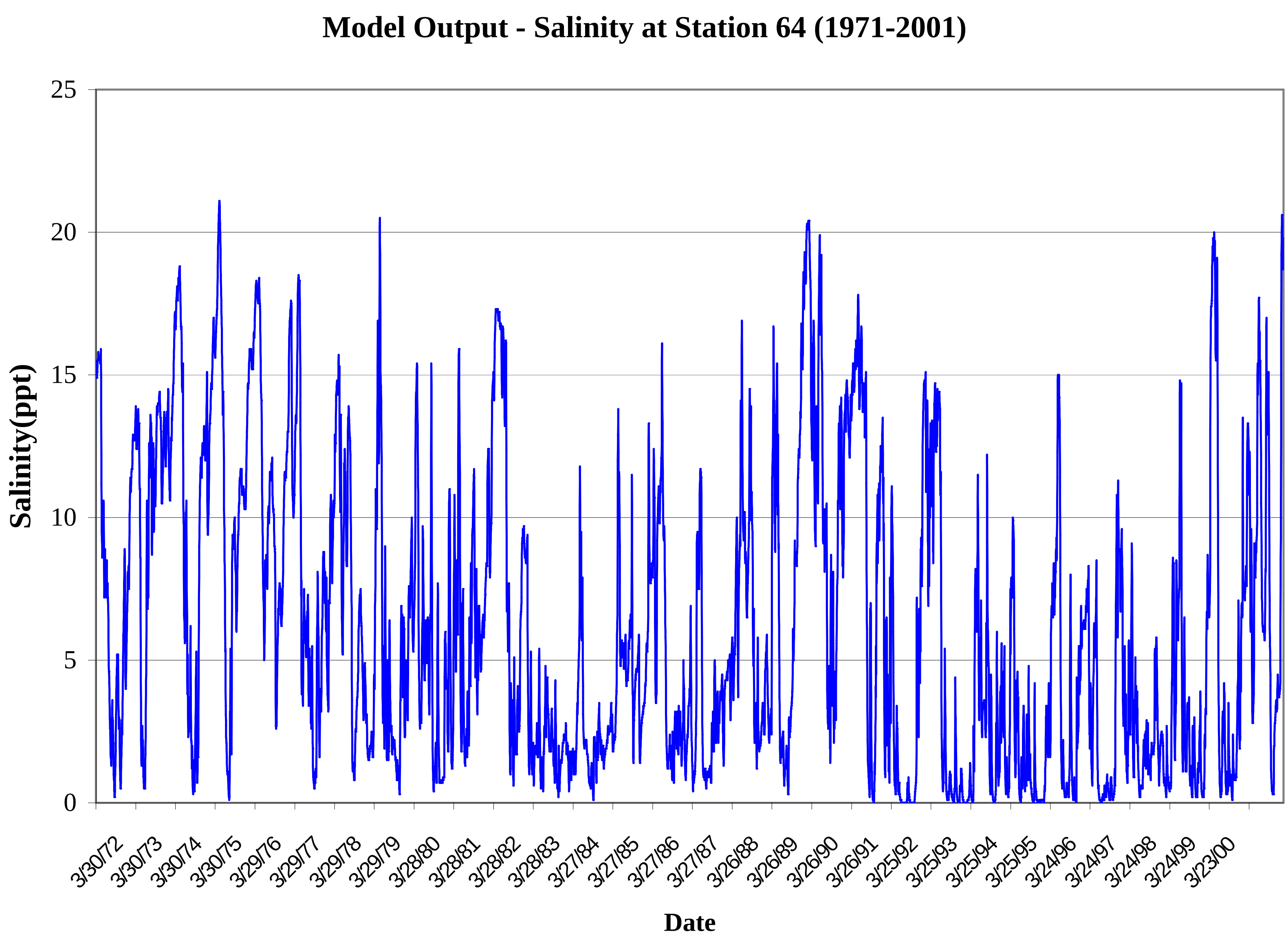


Figure 22. Model simulation of historic salinity condition (Station 64)

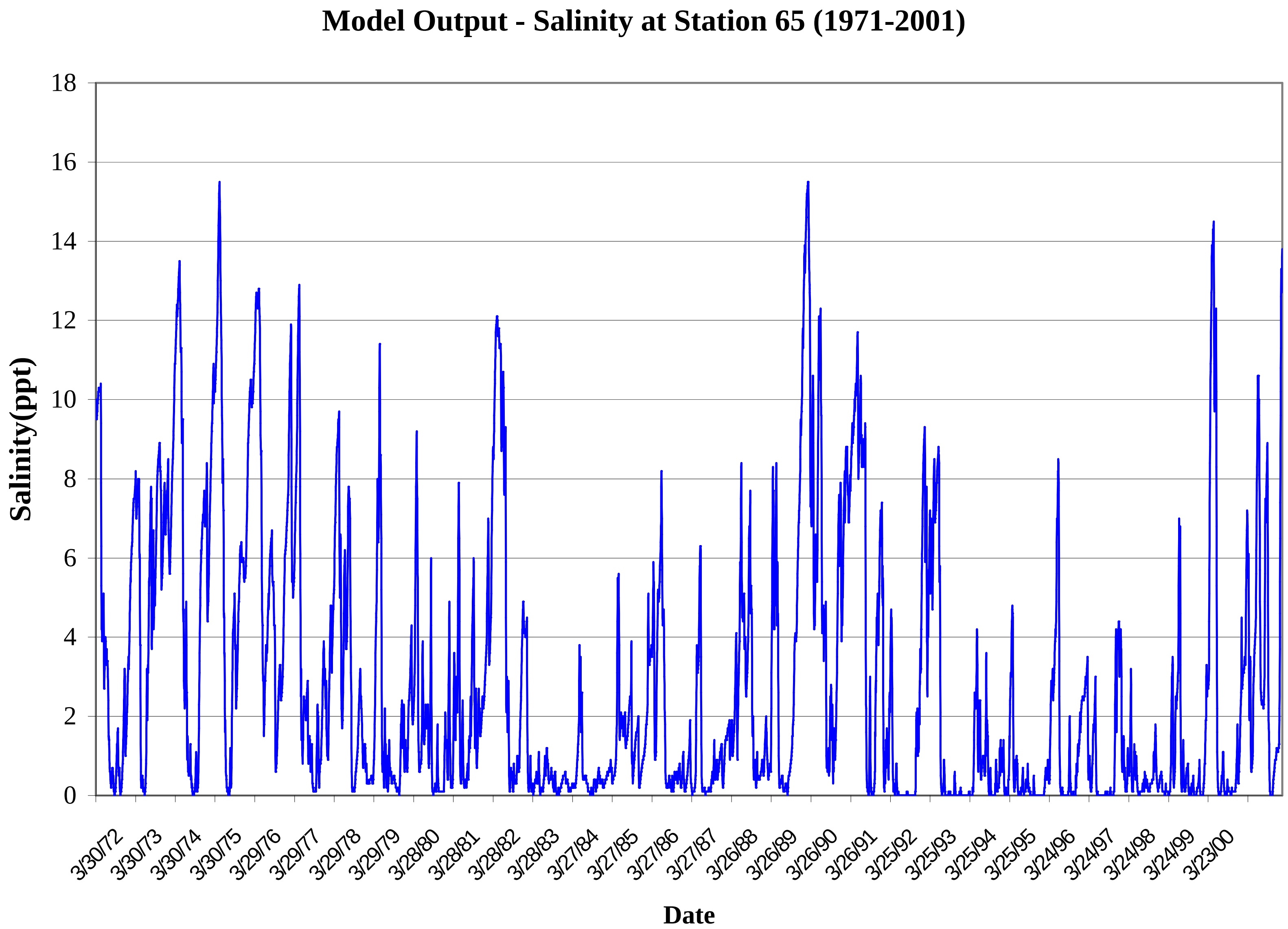


Figure 23. Model simulation of historic salinity condition (Station 65)